N O T I C E

Orbit Transfer Vehicle Engine Study
Phase A, Extension I

Contract NAS 8-32999
Advanced Expander Cycle
Engine Optimization
Task Report 32999E1-T1
November 1979

Prepared For:
George C. Marshall Space Flight Center
National Aeronautics And Space Administration
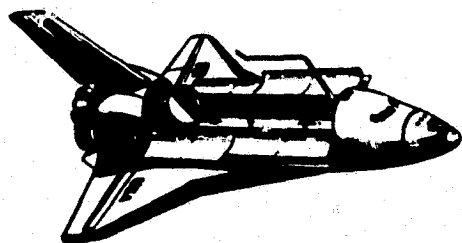
Aerojet
Liquid Rocket
Company

Report 32999 E1-T1

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ORBIT TRANSFER VEHICLE ENGINE STUDY
PHASE "A" EXTENSION 1

Contract NAS 8-32999

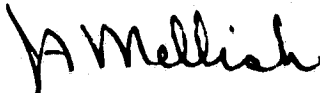Advanced Expander Cycle Engine Optimization

Task Report

Prepared for

George C. Marshall Space Flight Center
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FOREWORD

This task report is submitted for the Orbit Transfer Vehicle Engine Study, Phase "A", Extension 1 per the requirements of Contract NAS 8-32999. This work is being performed by the Aerojet Liquid Rocket Company for the NASA/Marshall Space Flight Center. The study authority to proceed was received on 20 July 1979.

The study program consists of engine system, programmatic, cost and risk analyses of OTV engine concepts. These evaluations will ultimately lead to the selection and conceptual design of the OTV engine for use by the OTV vehicle contractor.

The NASA/MSFC COR is Mr. D. H. Blount. The alternate COR is Mr. J. F. Thompson. The ALRC Program Manager is Mr. L. B. Bassham and the Study Manager is Mr. J. A. Mellish.

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I.   INTRODUCTION

A.   BACKGROUND

The Space Transportation System (STS) includes an Orbit Transfer Vehicle (OTV) that is carried into low Earth orbit by the Space Shuttle. The primary function of the OTV is to extend the STS operating regime beyond the Shuttle to include orbit plane changes, higher orbits, geosynchronous orbits and beyond. The NASA and the DOD have been studying various types of OTV's in recent years. Data have been accumulated from the analyses of the various concepts, operating modes and projected missions. The foundation formulated by these studies established the desirability and the benefits of a low operating cost, high performance, versatile OTV. The OTV must be reusable to achieve a low operating cost. It is planned that an OTV have an initial Operating Capability (IOC) in 1987.

The OTV has as a goal the same basic characteristics as the Space Shuttle, i.e., reusability, operational flexibility, and payload retrieval along with a high reliability and low operating cost. It is necessary to obtain sufficient data, of a depth to assure credibility, from which compara- tive systems analyses can be made to identify the performance, development, costs, risks and program requirements for OTV concepts. The maximum potential of each concept to satisfy the mission goals will be identified in the OTV systems studies initiated in FY-79.

This program is a continuation of a study of oxygen/hydrogen engines for OTV applications. This study extension will provide preliminary design data, plans and cost information which will complement the data gener- ated to satisfy the original Statement of Work on Contract NAS 8-32999, dated 6 July 1978. This engine data from the original and extension efforts, together with the system studies, will provide the basis to objectively select, define and design the preferred OTV engine.

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I, Introduction (cont.)

B.   OBJECTIVES

The major objectives of this Phase "A" engine study extension are: (1) optimize an advanced expander cycle engine for OTV applications, (2) investigate the feasibility of providing low-thrust capability within the same expander cycle engine, (3) provide additional safety, reliability, development risk, cost and planning data on OTV engine candidates, and (4) provide design and programmatic parametric data on the OTV engines for use by NASA and OTV system contractors. The original and engine study extension, in conjunction with the system studies, will provide comparative data on engine design alternatives and identify engine requirements, concepts and approaches recommended for further study on a subsequent conceptual design phase.

To accomplish the program objectives, a study program composed of five (5) major tasks and a reporting task is being conducted. The study tasks are:

    Task I: Advanced Expander Cycle Engine Optimization
    Task II: Alternate Low-Thrust Capability
    Task III: Safety, Reliability and Development Risk Comparison
    Task IV: Cost and Planning Comparison
    Task V: Vehicle Systems Studies Support

This report summarizes the results of Task I, Advanced Expander Cycle Engine Optimization.

II. ADVANCED EXPANDER CYCLE ENGINE OPTIMIZATION

The objective of this task was to optimize the performance of expander cycle engines at vacuum thrust levels of 10K, 15K, and 20K lb. This optimization was conducted for a maximum engine length with an extendible nozzle in the retracted position of 60 inches and an engine mixture ratio of 6.0:1. The information generated in this task will form the basis for an expander cycle engine point design.

The optimization reported upon herein consists of thrust chamber geometry and cycle analysis. In addition, the sensitivity of a recommended baseline expander cycle to component performance variations was determined and chilldown/ start propellant consumptions were estimated.

A. THRUST CHAMBER GEOMETRY OPTIMIZATION

This subtask consisted of heat transfer, cycle and performance/ weight tradeoff analyses to determine the effect the combustion chamber length and contraction ratio upon the cycle power balance, engine performance and engine weight.

Performance analyses have shown (Reference 1) that a minimum chamber length of about 12 inches is required to meet a Phase "A" ERE goal of 99.5%. Longer chambers lower the energy release loss, increase the hydrogen outlet temperature and increase the coolant jacket pressure drop. In some cases, the increased turbine inlet temperature can more than compensate for the increased pressure loss and result in higher thrust chamber pressure. For an engine with a fixed envelope (length), chamber pressure increases result in higher area ratios and hence, performance (I_s). Conversely, longer chambers reduce the length of the nozzle that can be fit in the fixed length constraint, thereby reducing the area ratio and performance. Longer chambers also result in heavier engine weights.

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II, A, Thrust Chamber Geometry Optimization (cont.)

The chamber contraction ratio has affects similar to those of chamber length. High chamber contraction ratios reduce the coolant jacket pressure drop and coolant outlet temperature (turbine inlet). Chamber contraction ratio increases also result in heavier chambers.

Heat transfer analyses were undertaken to establish the variation in the chamber coolant jacket pressure drop and coolant outlet temperature with combustion chamber length and contraction ratio. Baseline values selected during the initial study efforts, Ref. 1, were a chamber length of 18 inches and a contraction ratio of 3.66. These selections were based upon the results of analyses performed in other past contractural efforts (Refs. 2, 3 and 4).

Chamber contraction ratio and length (L') were varied in order that the tradeoffs among heat load, required pressure drop and nozzle area ratio (restricted by stowed length) could be used in system optimization studies. These studies were conducted at each thrust level for a range of chamber pressures as follows:

Thrust, lbf	Chamber Pressure psia
10K	1300 ± 200
15K	1200 ± 200
20K	1100 ± 200

The nominal chamber pressure values were selected during the initial Phase A (Ref. 1) efforts.

For each thrust and chamber pressure combination, chamber designs were generated as a function of L' (~12 to 30 inches) for contraction ratios of 2.32, 2.99, 3.66 and 5.0.

Design criteria and procedures used herein were identical to those used in the conduct of Task III of the original contract, Ref. (1). The channel widths in the cylindrical section were optimized for minimum pressure drop for each design (within a wall strength criterion which defines the maximum allowable channel width). This constraint was encountered in all designs with a contraction ratio of 5.0 and at the 15K and 20K thrust levels for a contraction ratio of 3.66. Channel depths are defined by the wall temperature limits associated with a cycle life of 300 cycles provided that the channel aspect ratio (depth/width) does not exceed 5:1. All chambers are one-pass designs with 85 percent of the total hydrogen flowing from area ratio 8:1 to the injector. The fixed portion of the nozzle, from an area ratio of 8:1 to the extendible nozzle attachment point is regeneratively cooled with the remaining 15 percent of the hydrogen flow. This fixed nozzle portion is a two-pass tube bundle design. The nozzle extension is a radiation cooled design.

Figures 1 through 4 present the chamber pressure drop results for the four contraction ratios considered in this study at the nominal thrust chamber pressures. Pressure drop is generally reduced with increasing thrust and contraction ratio. The exception occurs (Figure 5) at a contraction ratio of 5.0. This figure shows that the pressure drops for 20K lb thrust are slightly higher than those for 15K lb thrust. This occurs because the chamber channel designs at 20K lb thrust became aspect ratio (channel depth/width) limited at almost all axial locations. In all cases, the tube bundle nozzle pressure drops are very small (6 to 12 psi) and hence, the chamber pressure drop governs the engine pressure schedule.
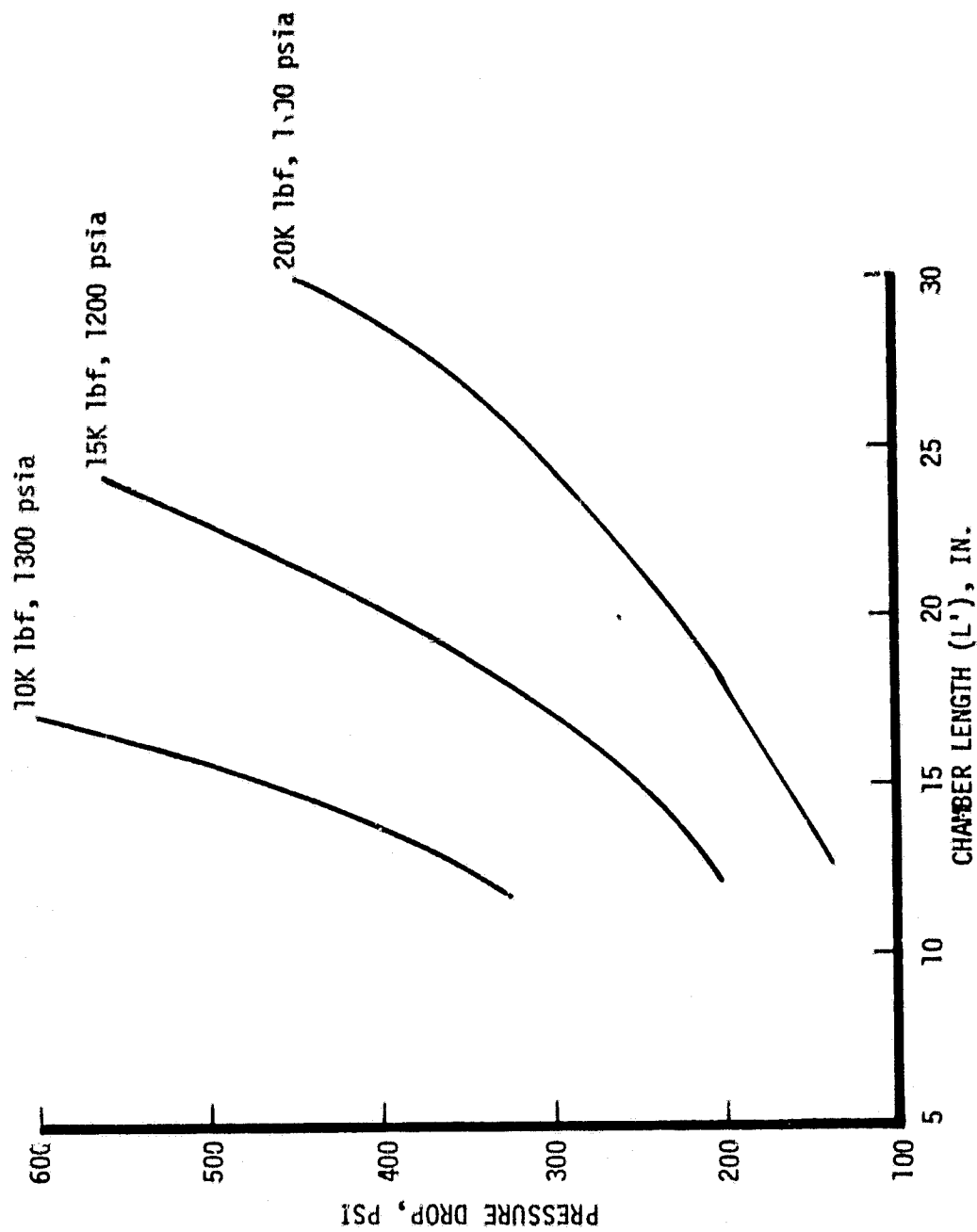
Figure 1. Chamber Pressure Drop Requirements, Contraction Ratio = 2.32
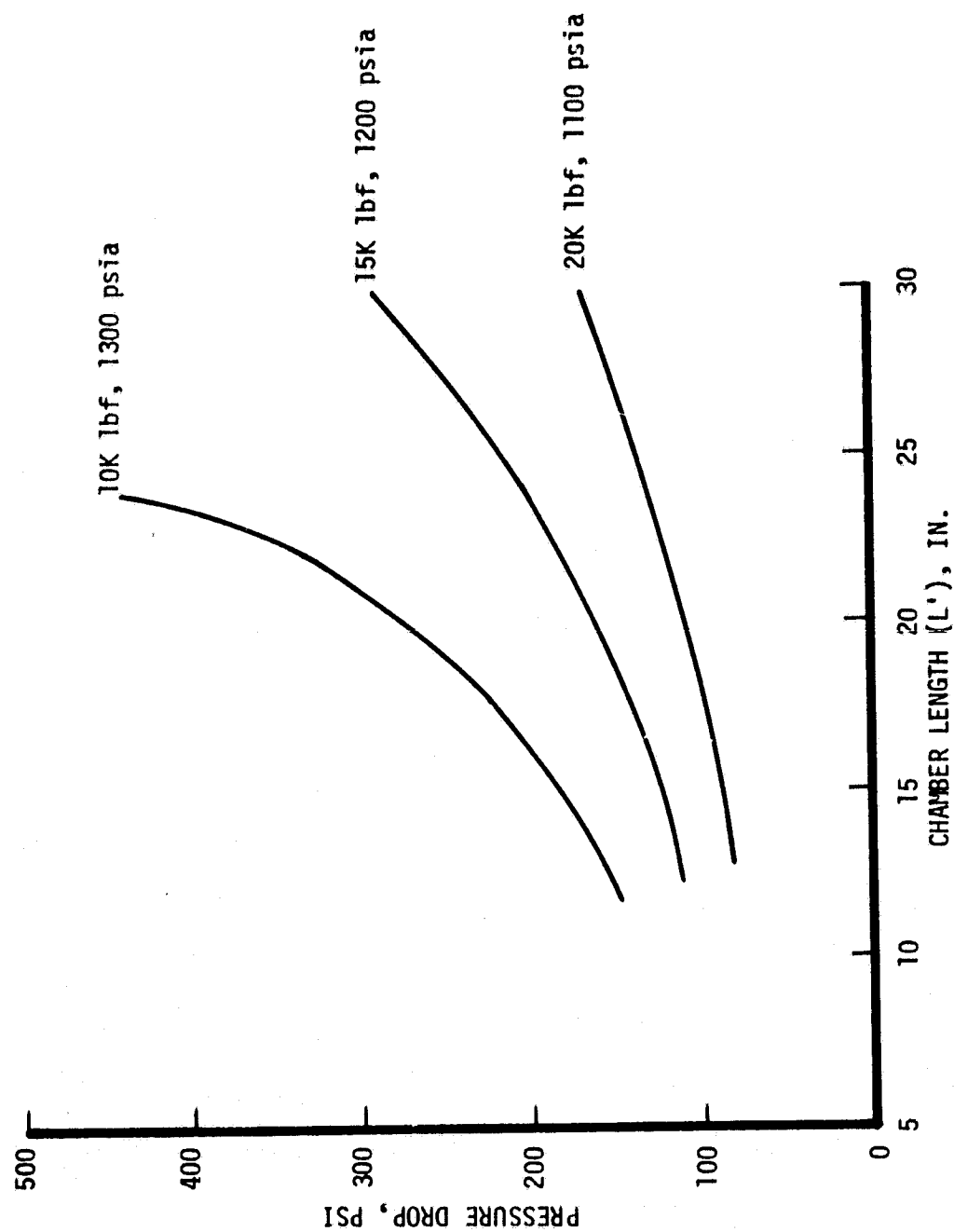
Figure 2. Chamber Pressure Drop Requirements, Contraction Ratio = 2.99
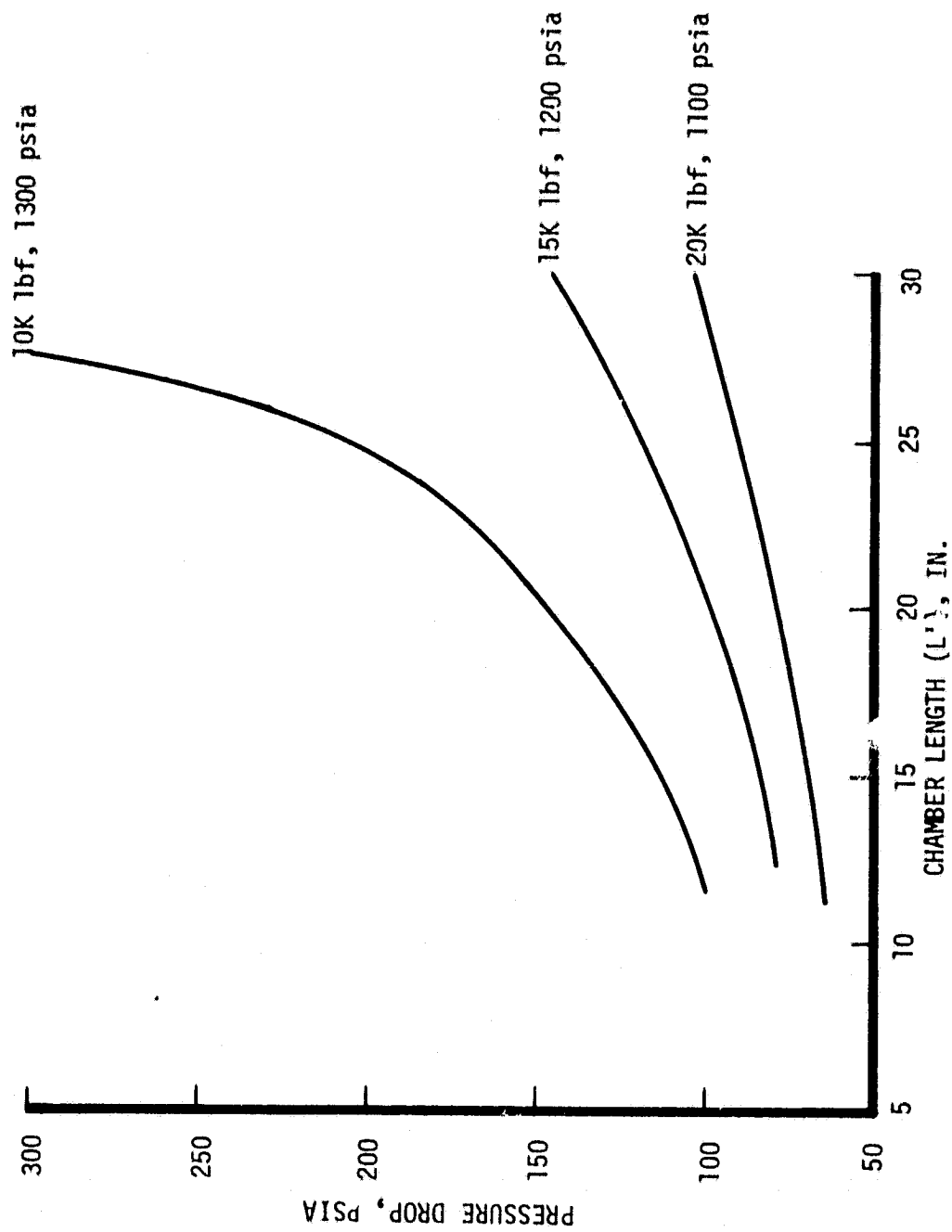
Figure 3. Chamber Pressure Drop Requirements, Contraction Ratio = 3.66

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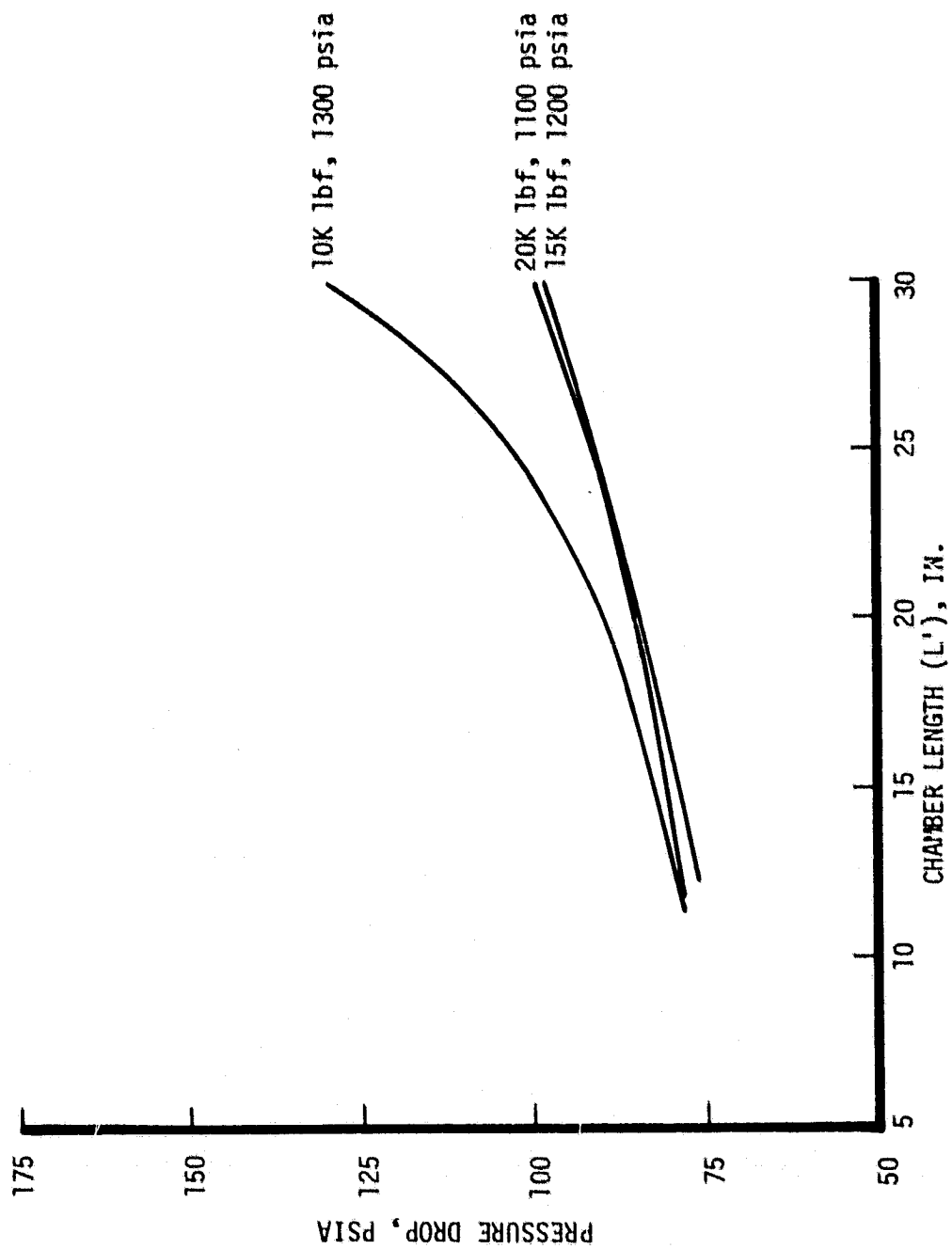
Figure 4. Chamber Pressure Drop Requirements, Contraction Ratio = 5.00

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II, A, Thrust Chamber Geometry Optimization (cont.)

The total turbine flow rate is the sum of the chamber and nozzle coolant flows. The turbine inlet temperature was determined by establishing the coolant bulk temperature rises in both the chamber and nozzle coolant jacket. Eighty-five percent of the hydrogen flow is used to cool the chamber and the remaining 15% is used to cool the fixed nozzle. The total nozzle heat load varies with L' because the cooled area ratio changes. The calculated turbine inlet temperatures are presented on Figures 5, 6, 7, and 8 for the four contraction ratios considered and at the baseline chamber pressure values. The data show that the turbine inlet temperature increases with reduced thrust and contraction ratio.

Engine cycle power balance analysis was performed, using the results of the heat transfer analyses, to establish the attainable chamber pressure as a function of chamber length and contraction ratio holding pump discharge pressure constant at the nominal values for each thrust level. Delivered performance and engine weight was then calculated at these chamber pressures. Weight and specific impulse tradeoffs were made by using the payload partials derived from NASA TMX-73394 (Ref. 5). These partials are:

	AMOTV	APOTV
$\Delta W_{PL}/\Delta I_S$, lb/sec	+73	+60
$\Delta W_{PL}/\Delta W_{ENG}$, lb/lb	-1.1	-1.1

The baseline engine cycle used in this portion of the study is a parallel turbine drive cycle which is shown by the simplified cycle schematic of Figure 9.

The results of the power balance and tradeoff analyses are displayed on Figures 10 through 18. The figures show that the baseline chamber length of 18 inches and a contraction ratio of 3.66 are either optimum or very nearly so at all thrust levels. Therefore, these values were used throughout the remaining study efforts.
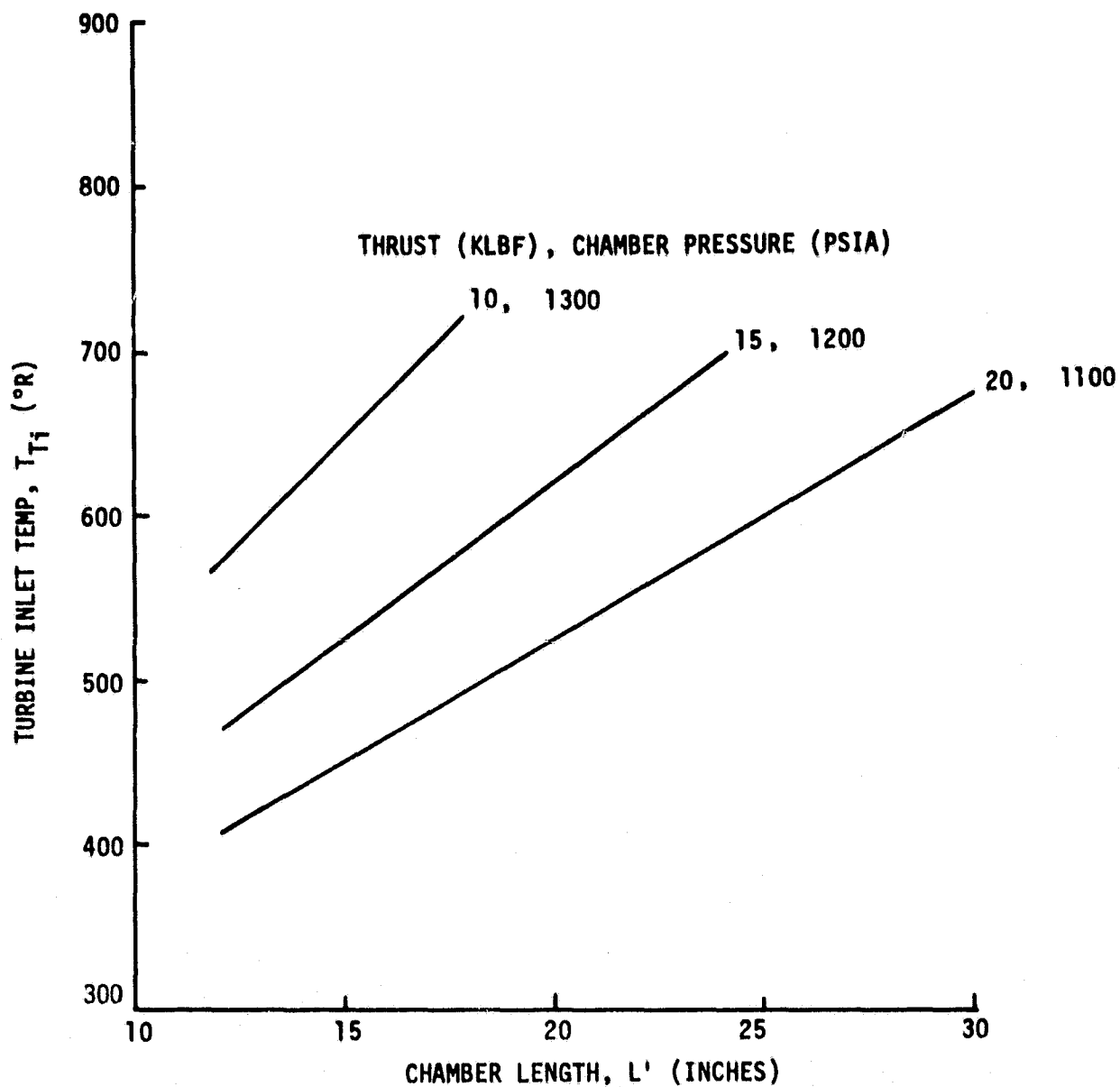
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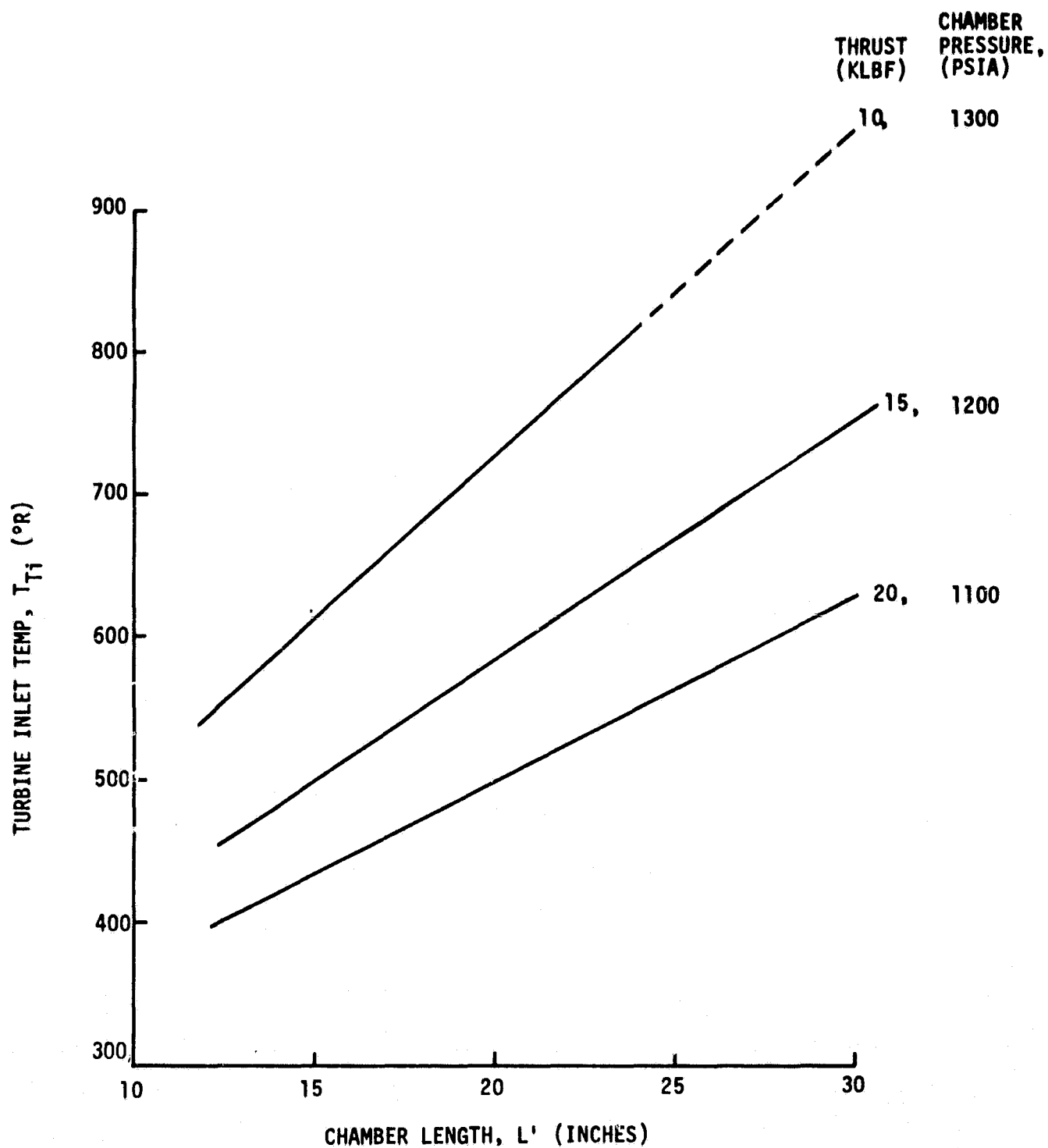
Figure 6.   Turbine Inlet Temperature vs Chamber Length
(Contraction Ratio = 2.99)
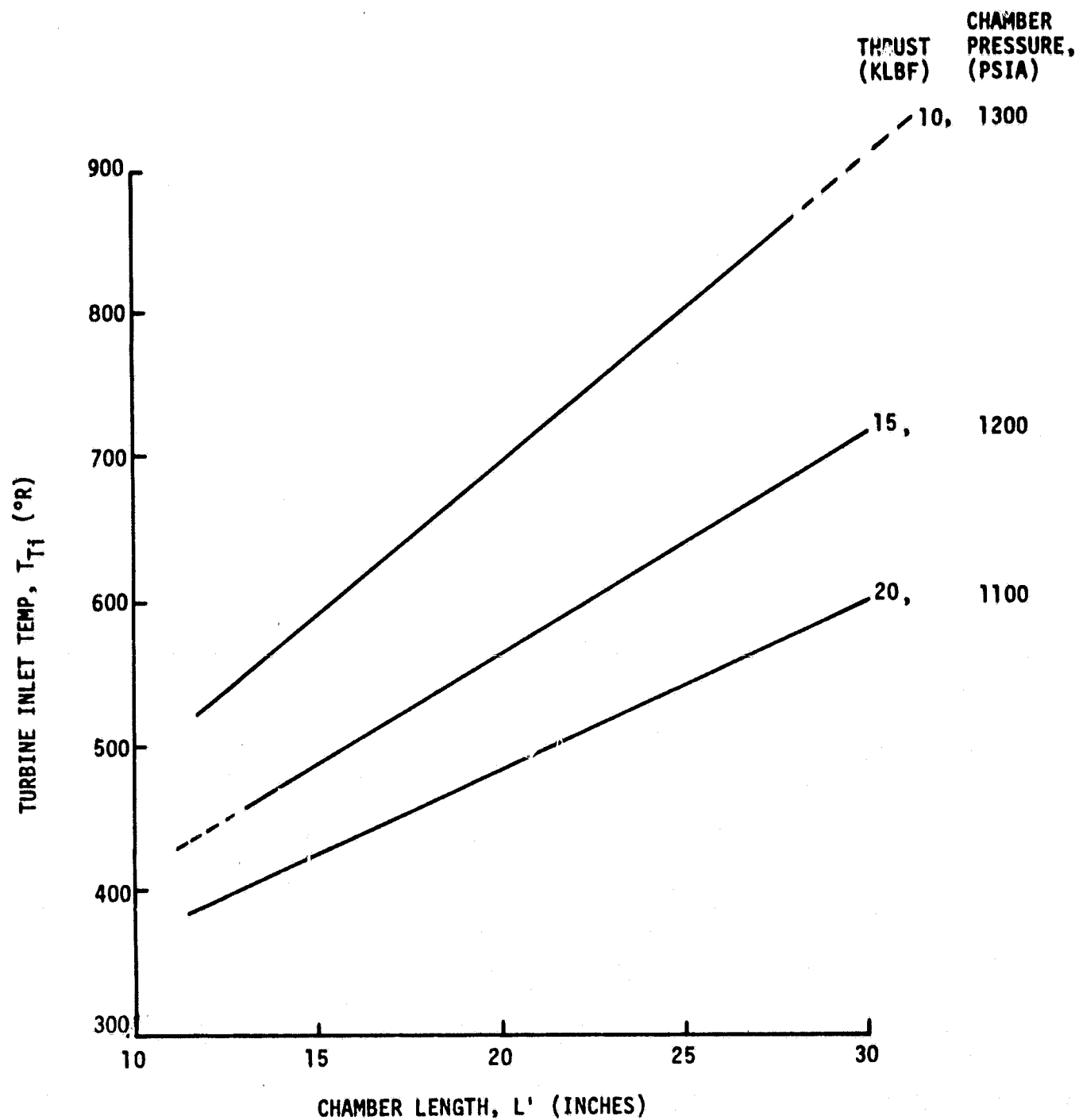
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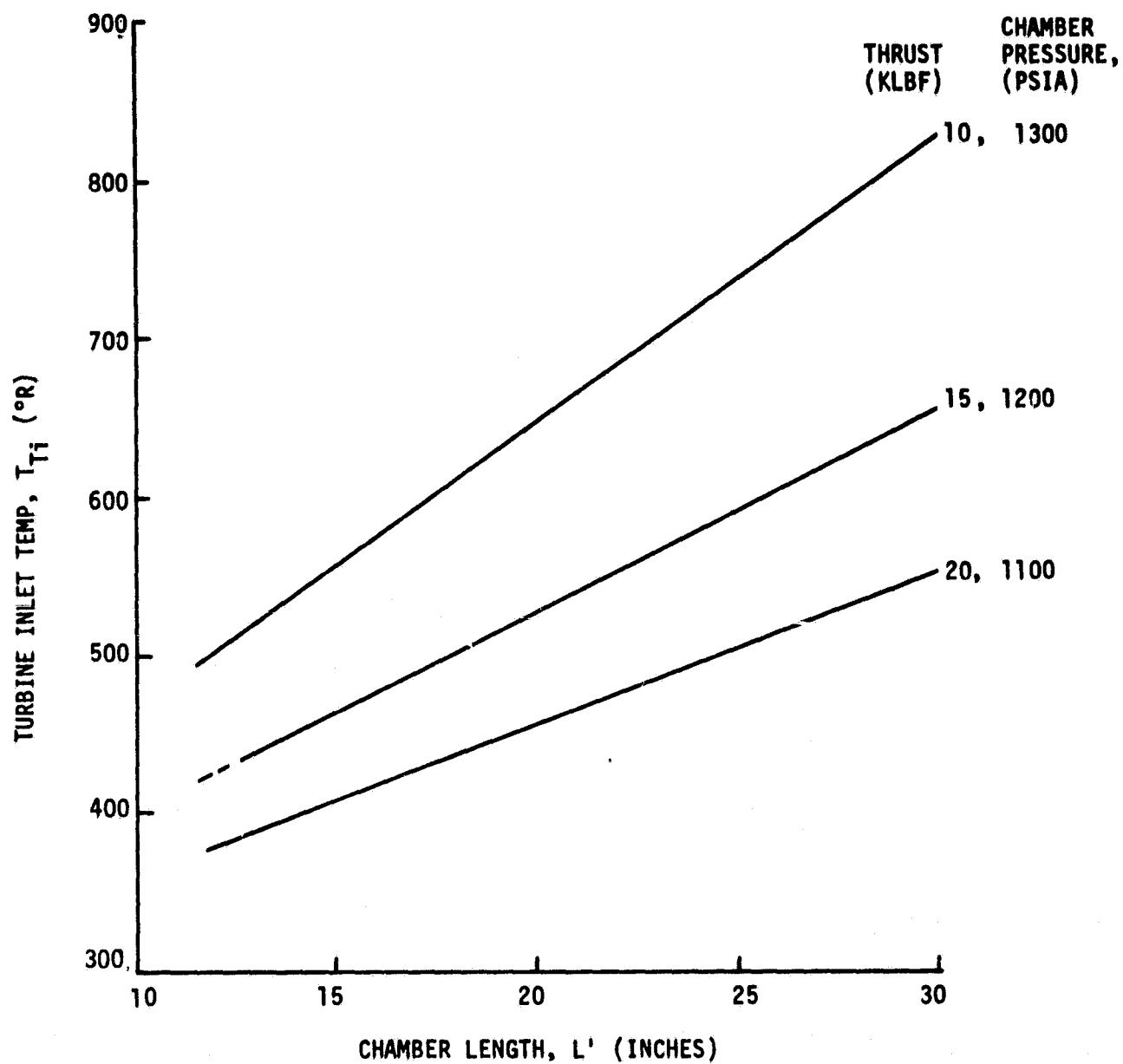
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P = PUMP
T = TURBINE
1 = LH2 SHUTOFF VALVE
2 = LOX SHUTOFF VALVE
3 = TURBINE BYPASS VALVE
4 = TURBINE FLOW CONTROL VALVE
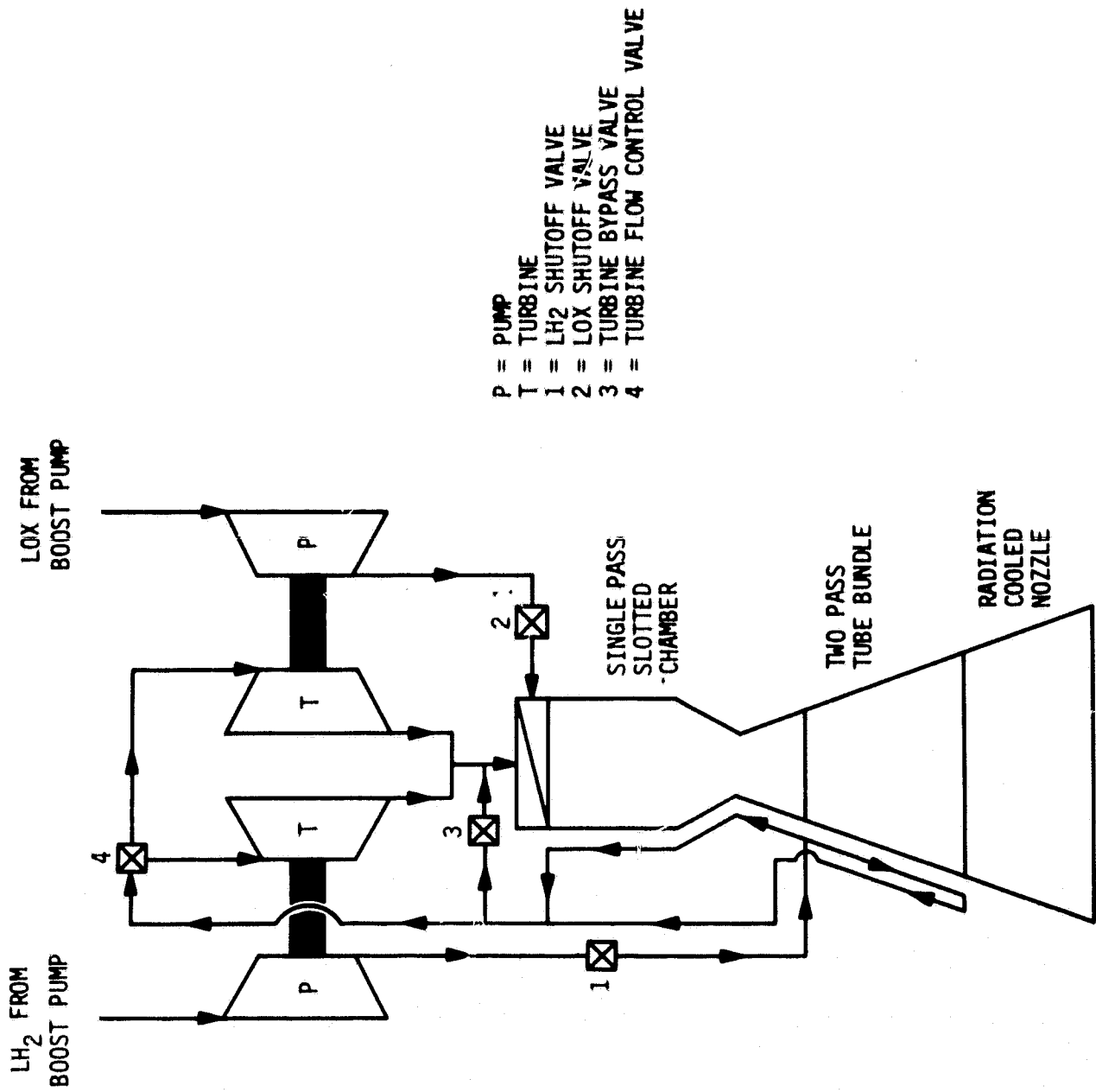
Figure 9. Parallel Turbines Advanced Expander Cycle Flow Schematic

CONTRACTION RATIO = 3.66
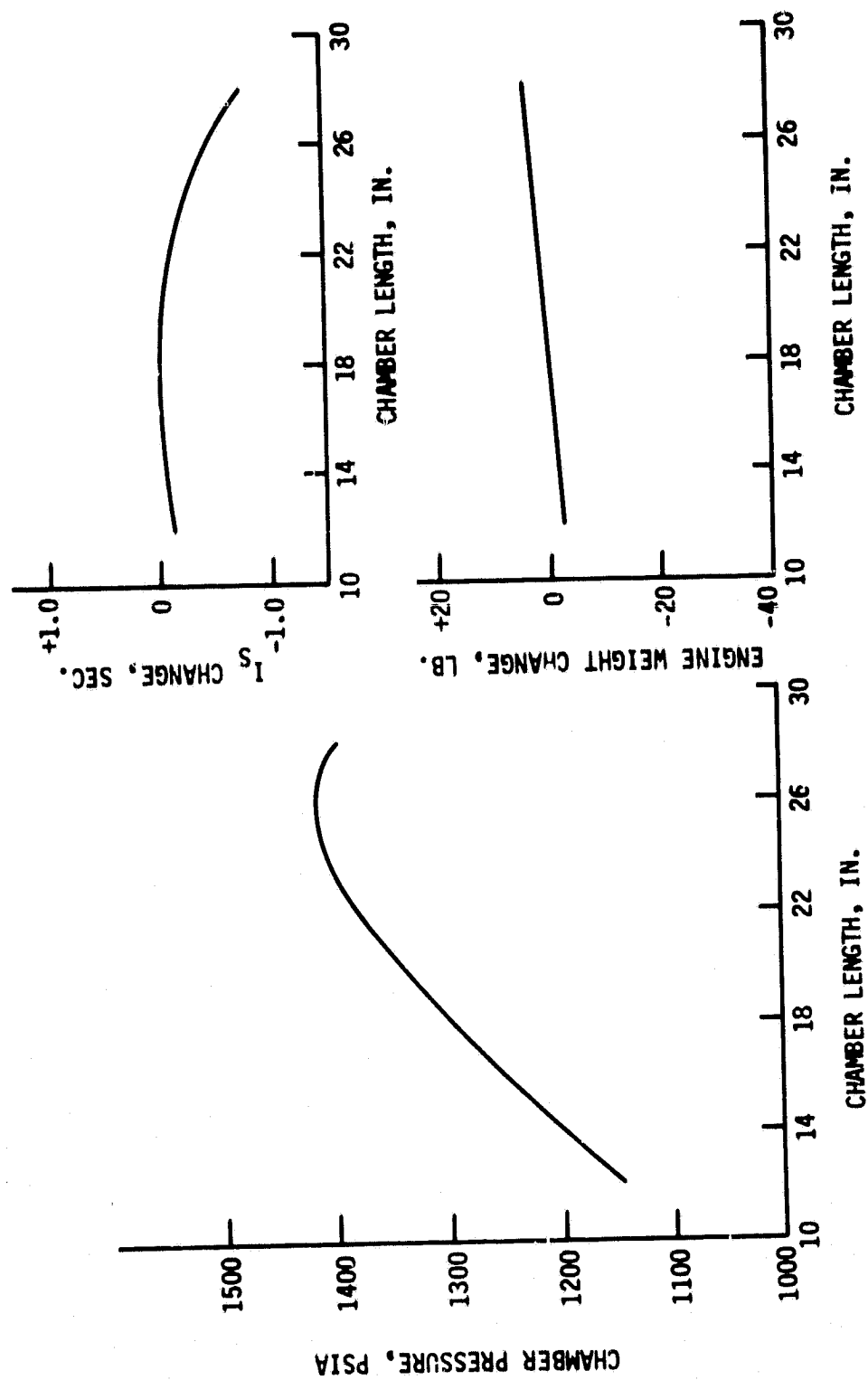
Figure 10. Chamber Length Effects at F = 10,000 lbF
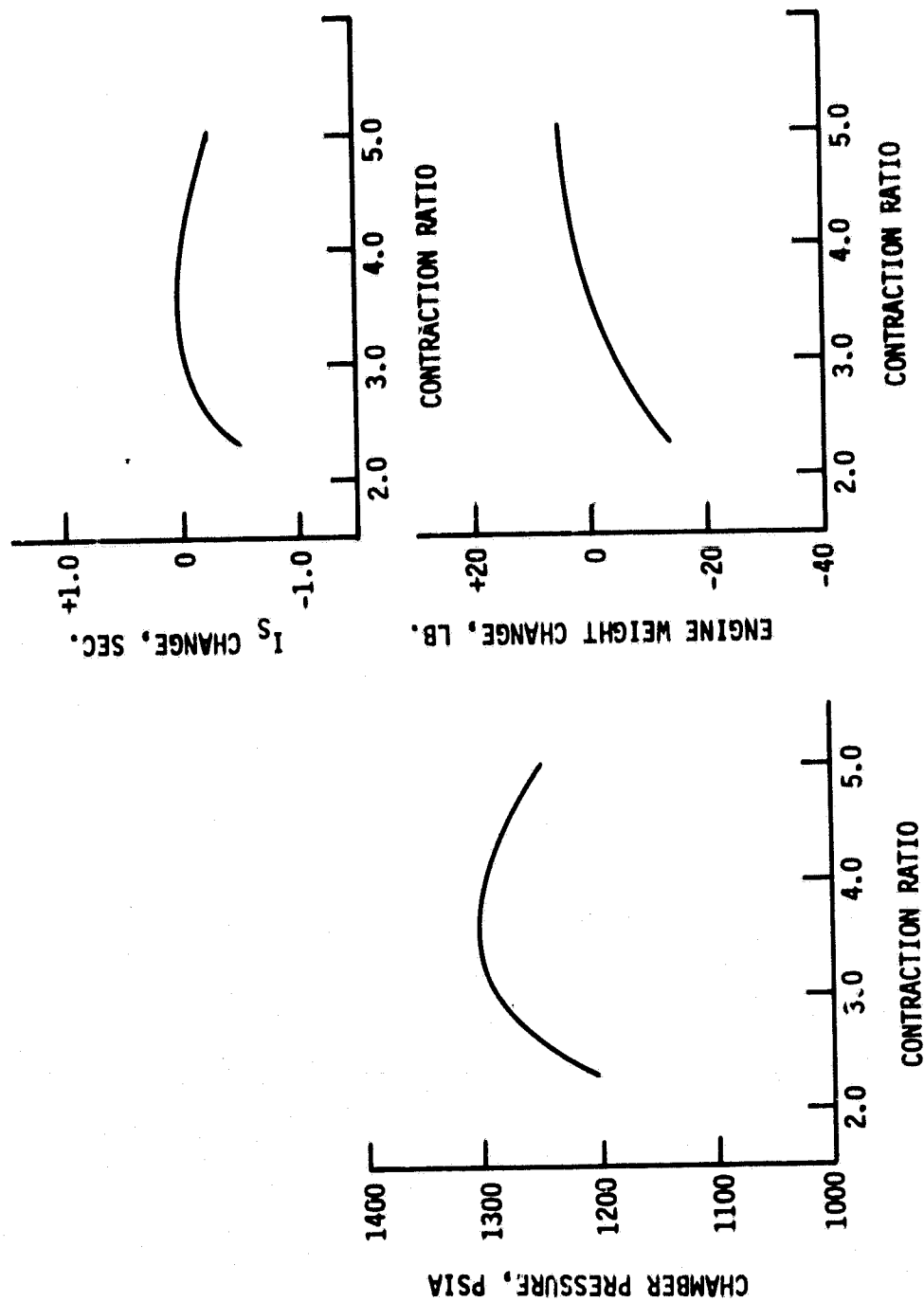
Figure 11. Contraction Ratio Effects at F = 10,000 lbF

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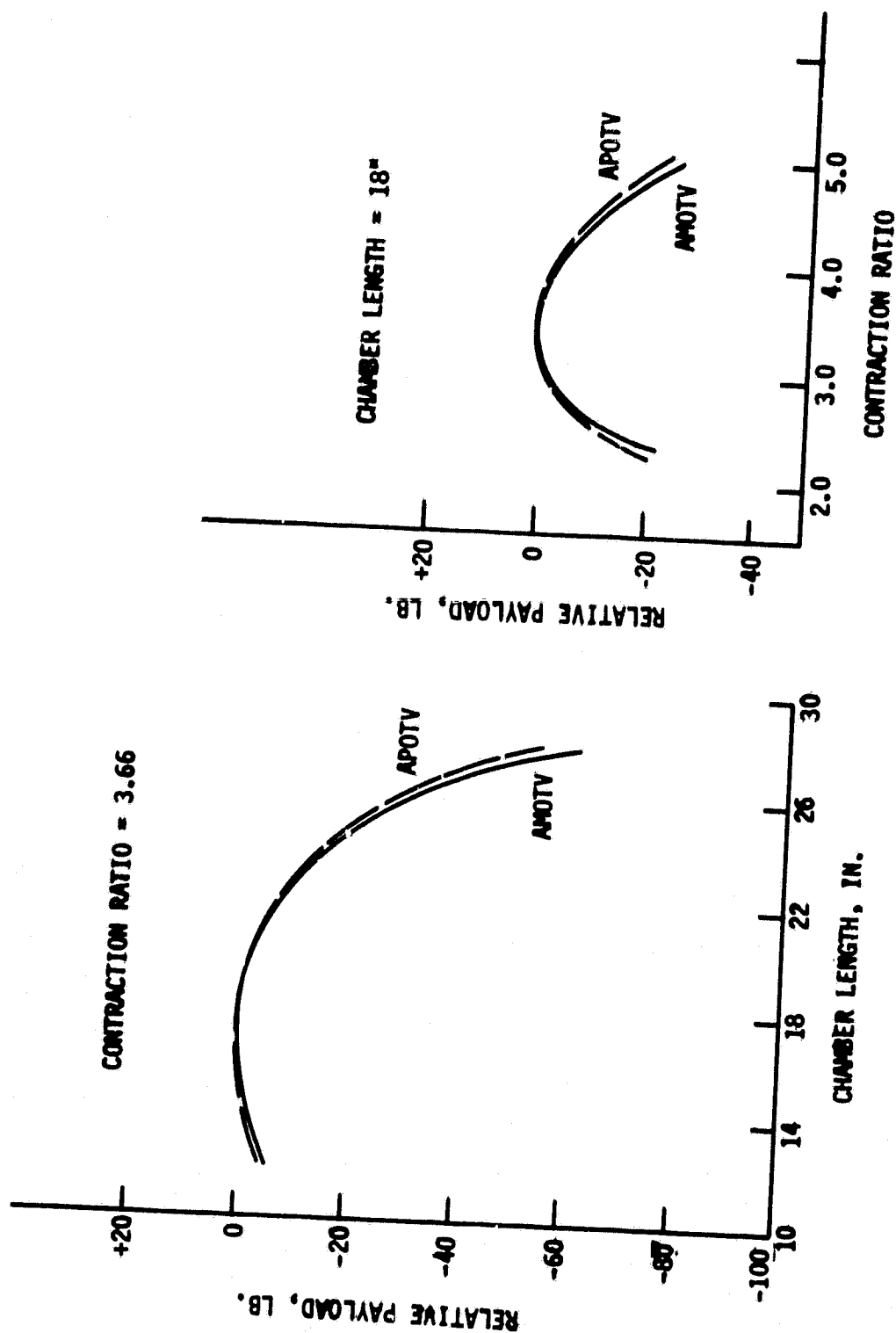
Figure 12. Chamber Length and Contraction Ratio Optimization at F = 10,000 lbF
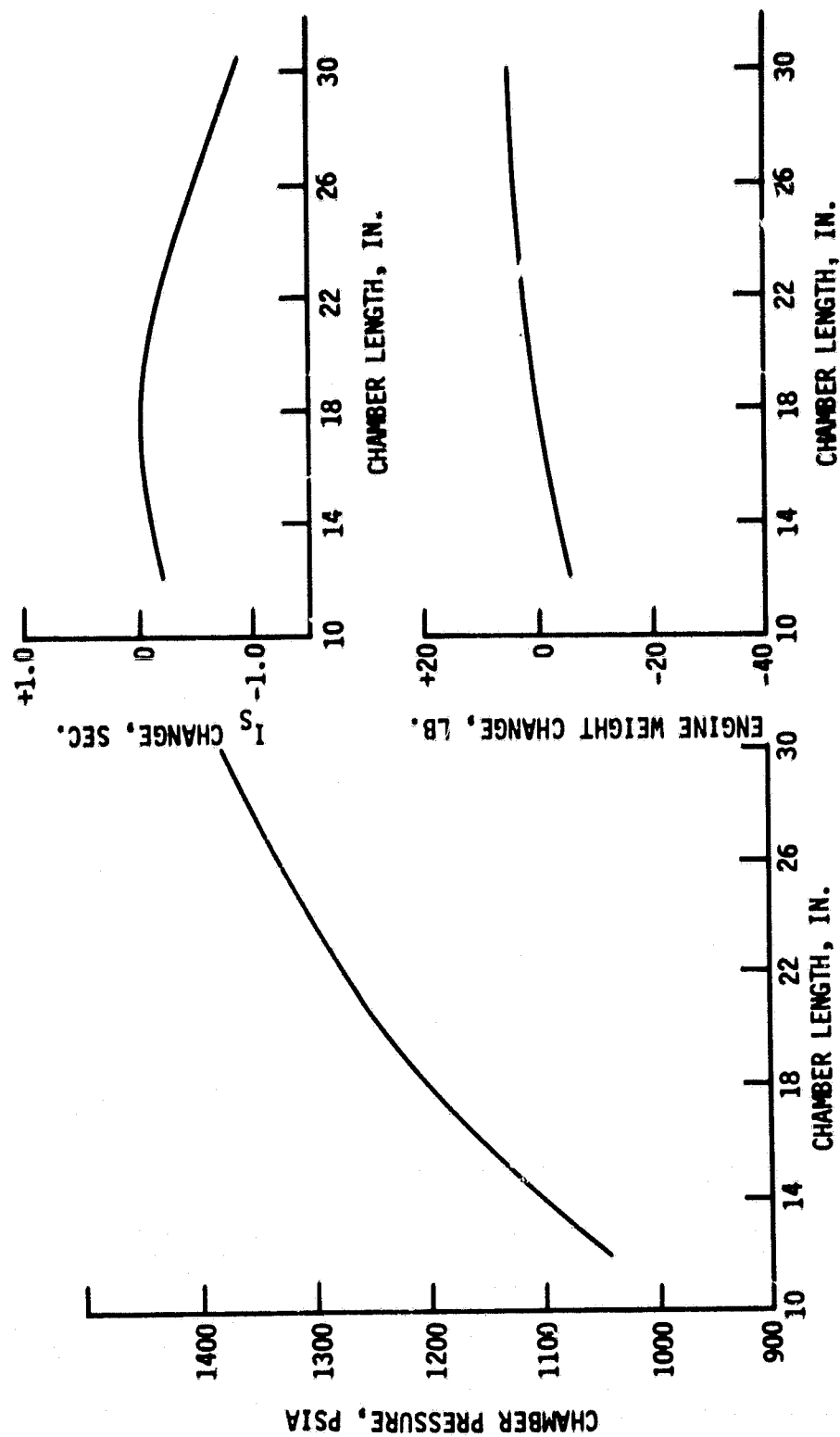
Figure 13. Chamber Length Effects at F = 15,000 lbF
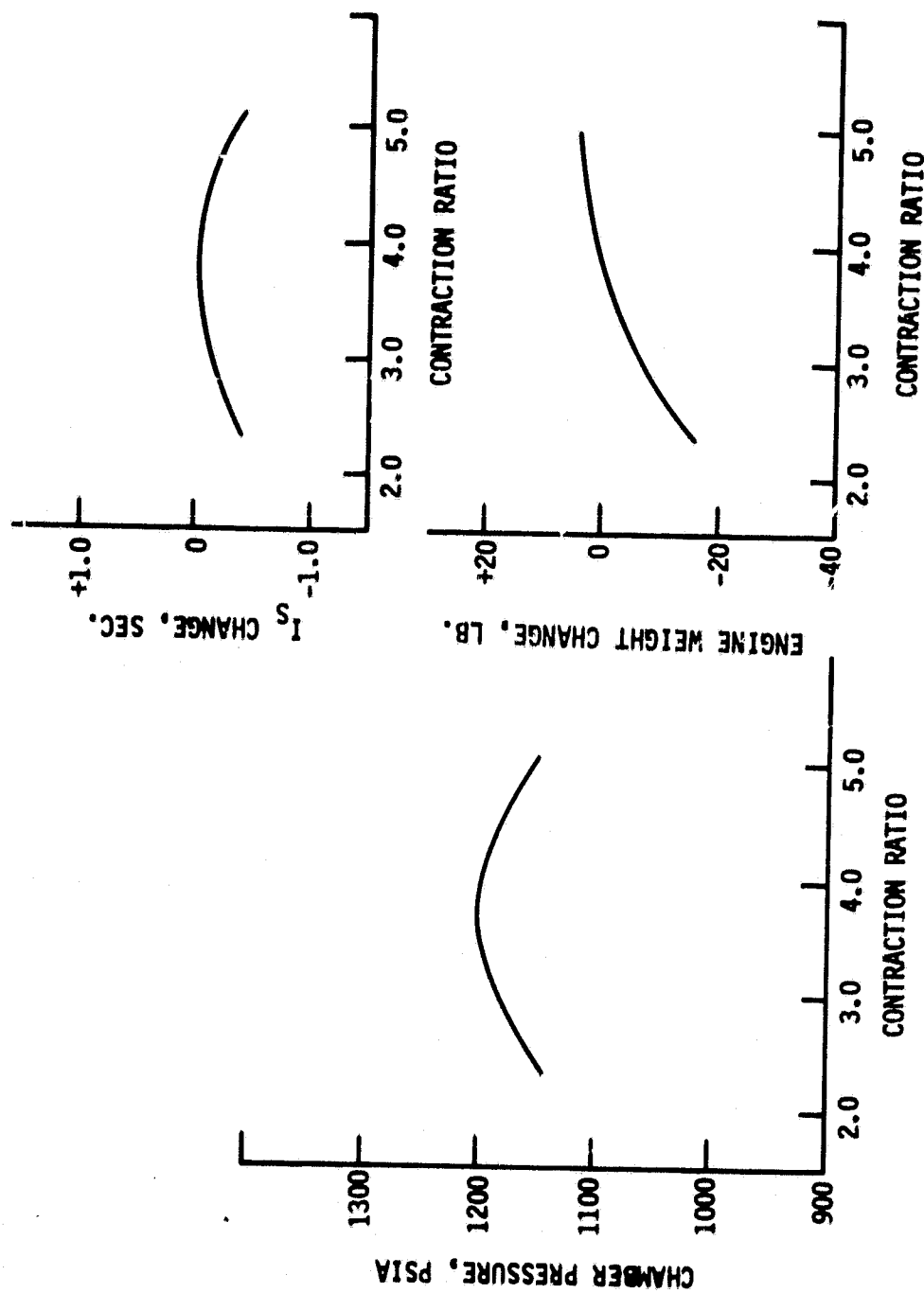
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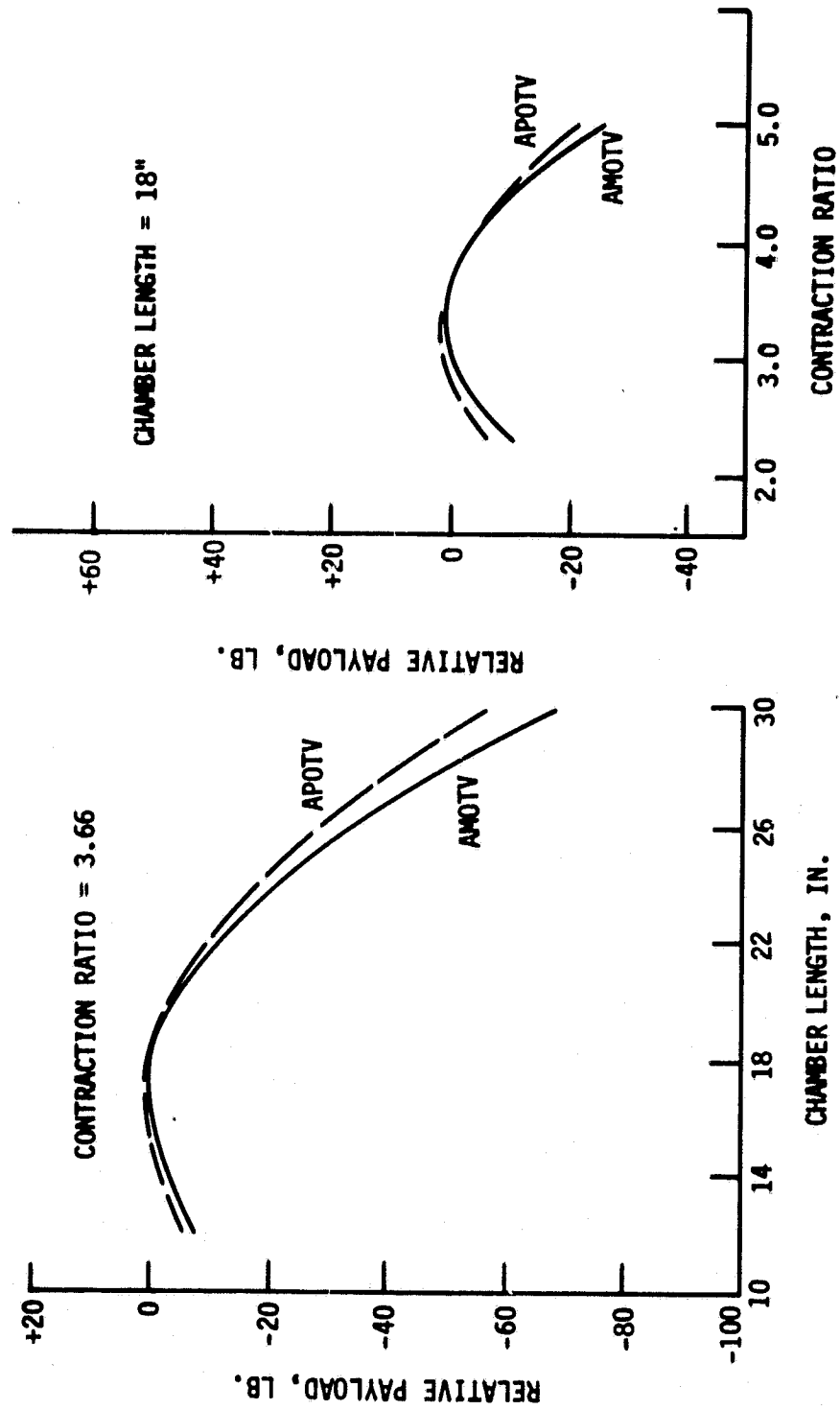
Figure 15. Chamber Length and Contraction Ratio Optimization at F = 15,000 lbF

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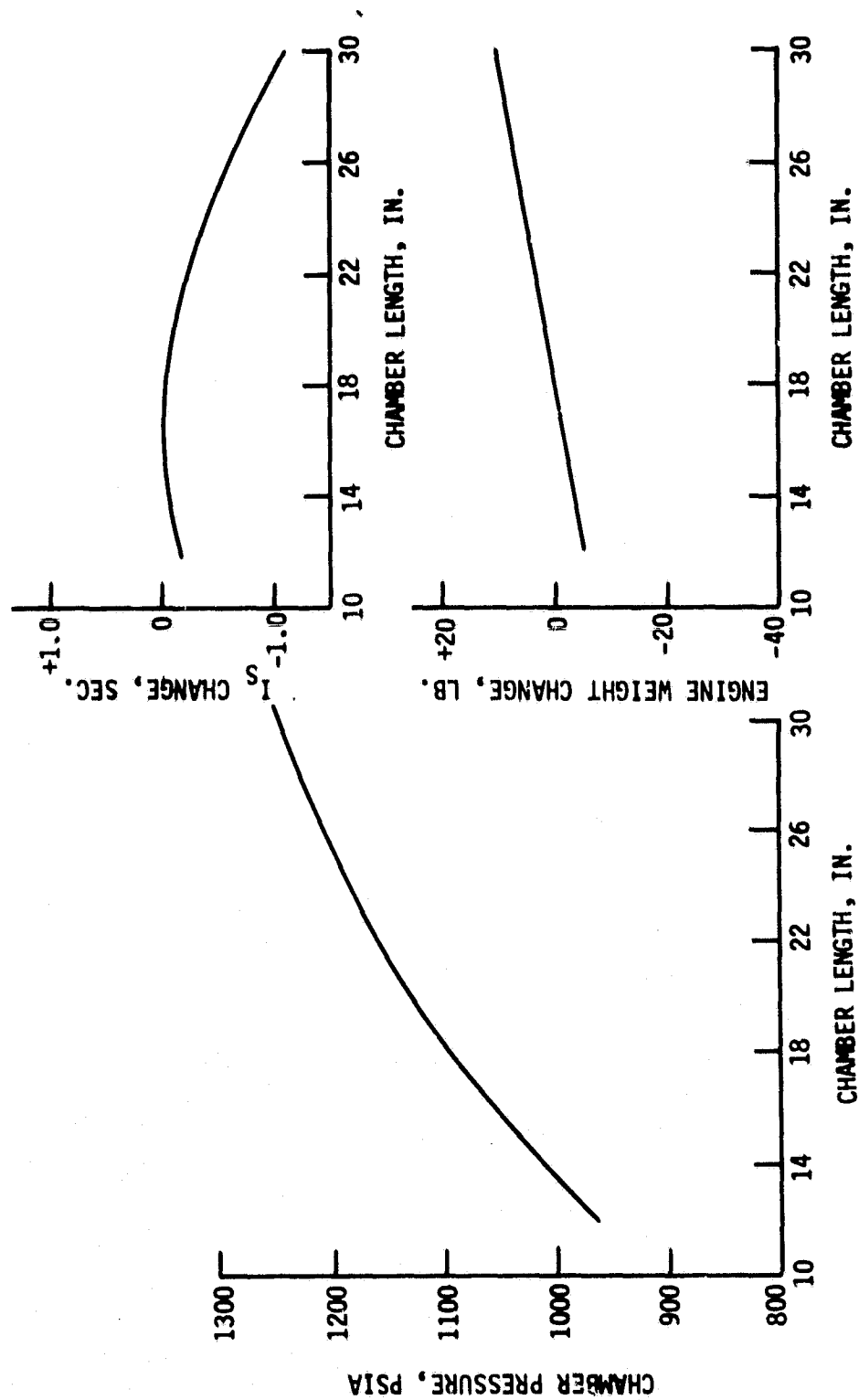
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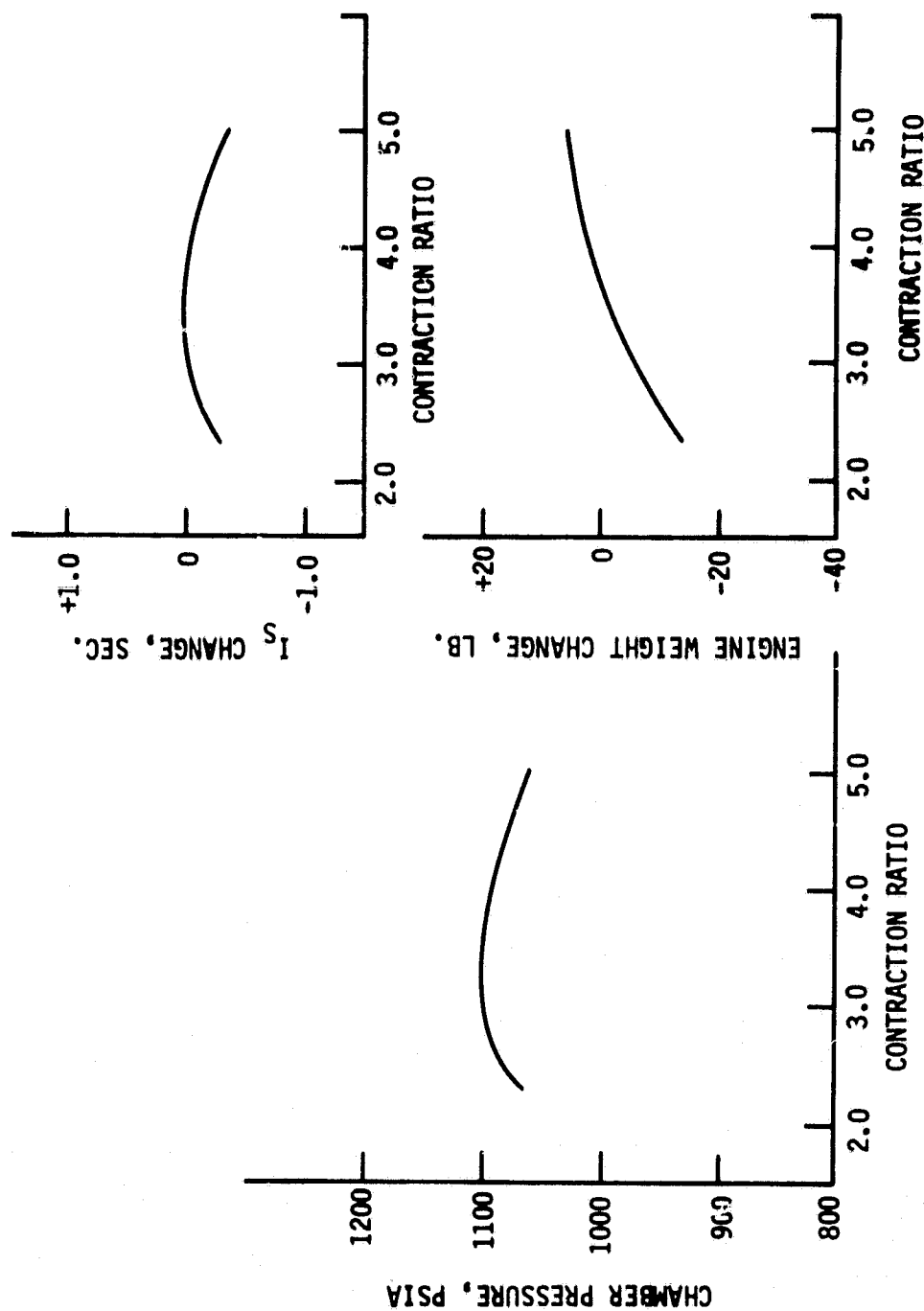
Figure 17. Contraction Ratio Effects at F = 20,000 lbF

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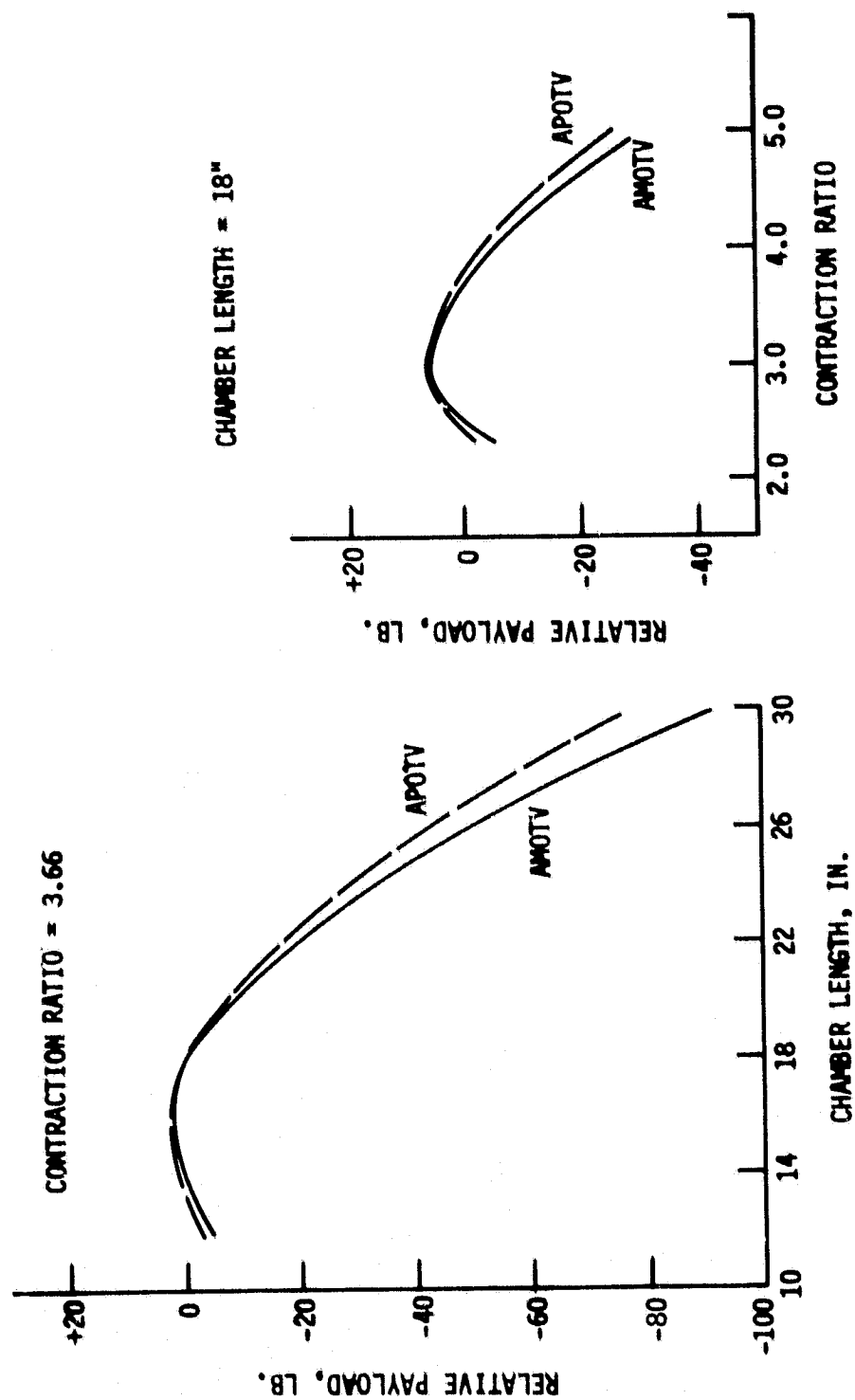
Figure 18. Chamber Length and Contraction Ratio Optimization at F = 20,000 lbF

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II, Advanced Expander Cycle Engine Optimization (cont.)

B.   CYCLE OPTIMIZATION

         The baseline expander engine cycle selected in the prior Phase
"A" study efforts was the parallel turbine drive concept previously shown on
Figure 9. Cycle variations were analyzed in this subtask to optimize the
engine. Concepts considered were: (1) series turbines drive, (2) turbine
exhaust heat regeneration, and (3) turbine exhaust reheat. Each of these
cycles is described and comparative analysis discussed in the following
paragraphs. Cycle power balance analyses were conducted for nominal chamber
pressure values of 1300, 1200, and 1100 psia at thrust levels of 10K, 15K
and 20K lb, respectively and also for fixed pump discharge pressures to
obtain higher chamber pressure levels.

         1.   Series vs Parallel Turbines

         The primary issue in these comparisons is whether the
higher flowrate, higher efficiency, series turbines can overcome the turbine
pressure drops being in series. A simplified flow schematic of the series
turbines arrangement is shown on Figure 19.

         To support the cycle power balance analyses, turbomachinery
analysis was conducted to obtain component efficiency data that is representa-
tive of the two turbine drive cycles. The efficiencies of the pump and
turbines were evaluated as a function of thrust level for both the parallel
and series turbine drive cycle cases. The results of this turbomachinery
analysis are shown in Figure 20. Cycle power balance analyses were then con-
ducted using this, efficiency data. The cycle power balances were initially
conducted for chamber pressures of 1300, 1200 and 1100 psia at thrust levels
of 10K, 15K and 20K lb, respectively. Cycles were first compared on the basis
of fuel pump discharge pressure requirements. The fuel circuit governs the
engine power balance. Therefore, the fuel pump discharge pressure level

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P = PUMP
T = TURBINE
1 = LH2 SHUTOFF VALVE
2 = LOX SHUTOFF VALVE
3 = TURBINE BYPASS VALVE
4 = TURBINE FLOW CONTROL VALVE

LOX FROM BOOST PUMP

LH₂ FROM BOOST PUMP

SINGLE PASS SLOTTED CHAMBER

TWO PASS TUBE BUNDLE

RADIATION COOLED NOZZLE
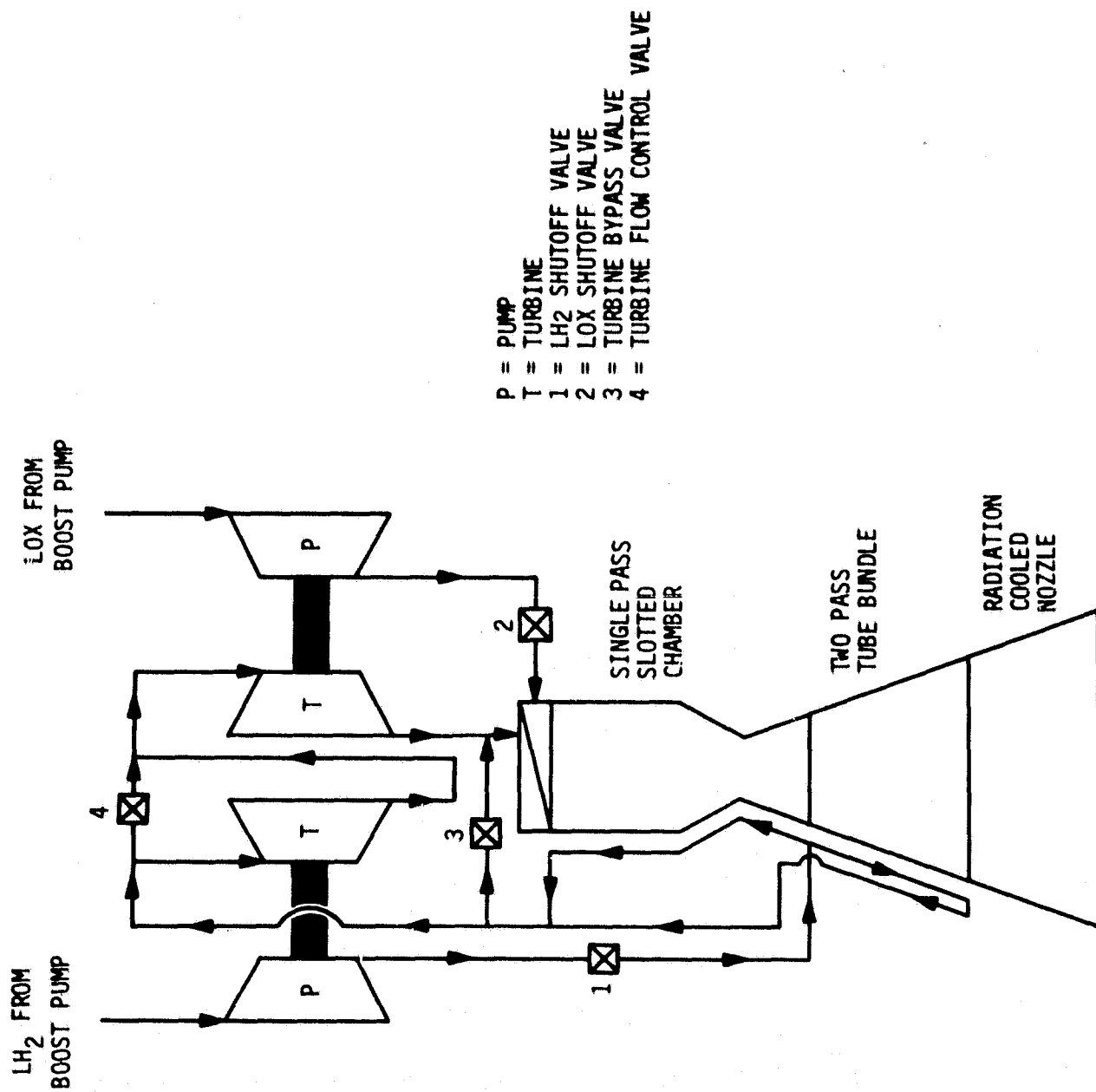
Figure 19. Series Turbines Advanced Expander Cycle Flow Schematic
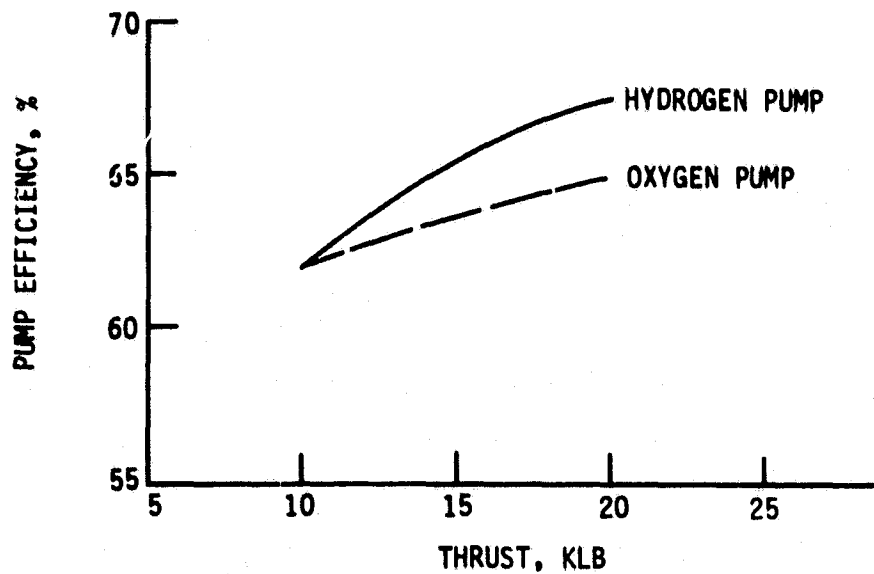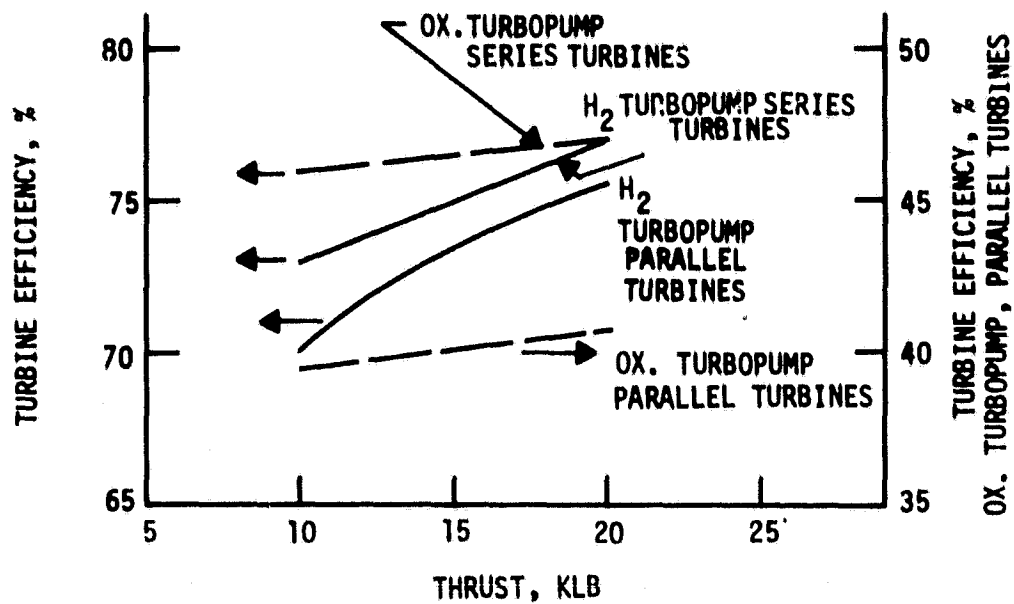
Figure 20.   Turbomachinery Efficiency Parametric Data

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II, B, Cycle Optimization (cont.)

indicates the ease in which the power balance can be obtained. Lower dis-
charge pressures also mean lower engine weight, although weight affects are
not significant enough to form the basis for a decision.

The parallel turbine power balance results are shown on
Tables I, II and III. The series turbines results are displayed on Tables IV,
V and VI. These tables show the engine system pressure schedule and the
parameters necessary to determine a cycle power balance. Although the boost
pumps were not evaluated in this analysis, the main oxidizer pump horsepower
has been increased by 5% and the main fuel pump horsepower has been increased
by 3% to account for the additional flowrate required to drive hydraulic boost
pump turbines. These horsepower penalties were calculated for the main pump
inlet pressure conditions shown on the tables. All pressures shown in the
power balance tables are total pressures. The turbine pressure ratio is
ratio of the turbine inlet total pressure to the turbine exit static pressure.
The outlet pressure is then converted to a total pressure.

The tables show that the series turbines arrangement has
much lower fuel pump discharge pressure requirements. This discharge pressure
is reduced by 850, 700 and 540 psia at thrust levels of 10K, 15K and 20K
lb, respectively, compared to the parallel turbine arrangement. These reduc-
tions in fuel pump discharge pressure requirements certainly appear to be
significant enough to warrant baselining a series, rather than a parallel
turbines arrangement. All power balances were conducted using a 6% turbine
bypass flowrate. With the series turbines arrangement, this flowrate could
be increased somewhat at the expense of fuel pump discharge pressure, to
provide more cycle margin and reduce the development risk.

The series turbines arrangement could also achieve a higher
operating chamber pressure and hence, higher area ratio and performance
within the fixed envelope constraint. Holding the fuel pump discharge
pressures constant at the values obtained for the parallel turbine arrange-
ment, the following results were obtained:

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TABLE I

PARALLEL TURBINES POWER BALANCE (F = 10K LB)

EXPANDER CYCLE
PARALLEL TURBINES
NO REHEAT
BOOST PUMPS

PRESSURE SCHEDULE (PSIA)

	FUEL CIRCUIT	LOX CIRCUIT
1.PUMP INLET	51.00	46.00
2.PUMP PRESSURE RISE	3494.48	1561.43
3.PUMP DISCHARGE	3545.48	1608.03
4.LINE PRESSURE DROP	10.00	25.00
5.VALVE INLET	3535.48	1583.03
6.VALVE PRESSURE DROP	35.35	15.83
7.VALVE OUTLEY	3500.13	1567.20
8.LINE PRESSURE DROP	30.00	--
9.COOLANT JACKET INLET	3470.13	--
10.COOLANT JACKET PRESSURE DROP	131.00	--
11.COOLANT JACKET OUTLET	3339.13	--
12.LINE PRESSURE DROP	20.00	--
12A.SPLITTER VALVE INLET	3319.13	--
12B.SPLITTER VALVE PRESSURE DROP	33.19	--
12C.SPLITTER VALVE EXIT	3285.94	--
12D.LINE PRESSURE DROP	10.00	--
13.TURBINE INLET	3275.94	--
14.TURBINE PRESSURE RATIO(PIN/POUT)	2.264	--
15.TURBINE OUTLET	1470.87	15.00
16.LINE PRESSURE DROP	36.77	1552.20
17.TCA INJECTOR INLET	1434.10	232.83
18.TCA INJECTOR PRESSURE DROP	114.73	232.83
19.TCA INJECTOR FACE	1319.37	1319.37
20.TCA PRESSURE DROP	19.37	19.37
21.CHAMBER PRESSURE	1300.00	1300.00

FLOWRATES (LBM/SEC)
TEMP DROP (DEGREES R)
CP(BTU/LB-R)
(FC=FUEL CIRCUIT)
(GC=CX CIRCUIT)
(T-S=TOTAL TT STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURBINE FLOW	2.15
2.OC TURBINE FLOW	.65
3.TURB INLET TEMP(T)	653.20
4.FC TURB T DROP(T-S)	136.20
5.OC TURB T DROP(T-S)	136.20
6.FC TURB EXIT T(T)	557.66
7.OC TURB EXIT T(T)	509.34
8.DRIVE GAS GAMMA	1.395
9.DRIVE GAS CP	3.530

HORSEPOWERS
AND EFFICIENCIES

(FC=FUEL CIRCUIT)
(GC=OX CIRCUIT)
(T-S=TOTAL TO STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURB HORSEPOWER	1023.02
2.OC TURB HORSEPOWER	173.50
3.FUEL PUMP SHP	1023.02
4.OX PUMP SHP	173.50
5.FC TURB EFF	.700
6.OC TURB EFF	.394
7.FUEL PUMP EFF	.620
8.OX PUMP EFF	.620
9.TOTAL FUEL FLOW	2.97
10.TOTAL OX FLOW	17.85
11.TURBINE BYPASS FLOW	.78

TABLE II

PARALLEL TURBINES POWER BALANCE (F = 15K LB)

EXPANDER CYCLE
PARALLEL TURBINES
NO REHEAT
BOOST PUMPS

PRESSURE SCHEDULE (PSIA)

	FUEL CIRCUIT	LOX CIRCUIT
1. PUMP INLET	51.00	46.00
2. PUMP PRESSURE RISE	3123.13	1440.83
3. PUMP DISCHARGE	3174.13	1487.43
4. LINE PRESSURE DROP	10.00	25.00
5. VALVE INLET	3164.13	1462.43
6. VALVE PRESSURE DROP	31.00	14.62
7. VALVE OUTLET	3132.48	1447.80
8. LINE PRESSURE DROP	30.00	--
9. COOLANT JACKET INLET	3102.48	--
10. COOLANT JACKET PRESSURE DROP	92.00	--
11. COOLANT JACKET OUTLET	3010.48	--
12. LINE PRESSURE DROP	20.00	--
12A. SPLITTER VALVE INLET	2990.48	--
12B. SPLITTER VALVE PRESSURE DROP	29.90	--
12C. SPLITTER VALVE EXIT	2960.58	--
12D. LINE PRESSURE DROP	10.00	--
13. TURBINE INLET	2950.58	--
14. TURBINE PRESSURE RATIO(PIN/POUT)	2.220	--
15. TURBINE OUTLET	1357.73	15.00
16. LINE PRESSURE DROP	33.96	--
17. TCA INJECTOR INLET	1323.78	1432.80
18. TCA INJECTOR PRESSURE DROP	105.90	214.92
19. TCA INJECTOR FACE	1217.88	1217.88
20. TCA PRESSURE DROP	17.88	17.88
21. CHAMBER PRESSURE	1200.00	1200.00

FLOWRATES (LBM/SEC)
TEMP DROP (DEGREES K)
CP(BTU/LB-R)
(FC=FUEL CIRCUIT)
(OC=OX CIRCUIT)
(T-S=TOTAL TO STATIC TEMP)
(T=TOTAL TEMP)

1. FC TURBINE FLOW	3.17
2. OC TURBINE FLOW	1.05
3. TURBINE INLET TEMP(T)	535.00
4. FC TURB T DROP(T-S)	108.63
5. OC TURB T DROP(T-S)	108.63
6. FC TURB EXIT T(T)	455.27
7. OC TURB EXIT T(T)	491.55
8. DRIVE GAS GAMMA	1.395
9. DRIVE GAS CP	3.652

HORSEPOWERS
AND EFFICIENCIES

(FC=FUEL CIRCUIT)
(OC=OX CIRCUIT)
(T-S=TOTAL TO STATIC TEMP)
(T=TOTAL TEMP)

1. FC TURB HORSEPOW	1306.3#
2. OC TURB HORSEPOW	235.57
3. FUEL PUMP SHP	1306.3#
4. OX PUMP SHP	235.57
5. FC TURB EFF	.734
6. OC TURB EFF	.400
7. FUEL PUMP EFF	.655
8. OX PUMP EFF	.636
9. TOTAL FUEL FLOW	8.49
10. TOTAL OX. FLOW	26.94
11. TURBINE BYPASS FLOW	.27

TABLE III

PARALLEL TURBINES POWER BALANCE (F = 20K LB)

EXPANDER CYCLE
PARALLEL TURBINES
NO REHEAT
BUCSI PUMPS

PRESSURE SCHEDULE (PSIA)

	FUEL CIRCUIT	LCX CIRCUIT
1.PUMP INLET	51.00	46.60
2.PUMP PRESSURE RISE	2713.20	1320.22
3.PUMP DISCHARGE	2764.20	1366.82
4.LINE PRESSURE DROP	10.00	25.00
5.VALVE INLET	2754.20	1341.82
6.VALVE PRESSURE DROP	27.54	13.42
7.VALVE OUTLET	2726.66	1328.40
8.LINE PRESSURE DROP	30.00	---
9.COOLANT JACKET INLET	2696.66	---
10.COOLANT JACKET PRESSURE DROP	76.00	---
11.COOLANT JACKET OUTLET	2620.66	---
12.LINE PRESSURE DROP	20.00	---
12A.SPLITTER VALVE INLET	2600.66	---
12B.SPLITTER VALVE PRESSURE DROP	26.01	---
12C.SPLITTER VALVE EXIT	2574.65	---
12D.LINE PRESSURE DROP	10.00	---
13.TURBINE INLET	2564.65	---
14.TURBINE PRESSURE RATIO(PIN/PLLT)	2.115	---
15.TURBINE OUTLET	1244.52	15.00
16.LINE PRESSURE DROP	31.11	1313.40
17.TCA INJECTOR INLET	1213.47	197.61
18.TCA INJECTOR PRESSURE DROP	97.08	1116.39
19.TCA INJECTOR FACE	1116.39	16.39
20.TCA PRESSURE DROP	16.39	1100.00
21.CHAMBER PRESSURE	1100.00	

FLOWRATES (LBM/SEC)
TEMP DROP (DEGREES R)
CP(BTU/LB-R)
(FC=FUEL CIRCUIT)
(CC=OX CIRCUIT)
(T-S=TOTAL TO STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURBINE FLOW	4.17
2.OC TURBINE FLOW	1.49
3.TURB INLET TEMP(T)	463.00
4.FC TURB T DROP(T-S)	87.79
5.OC TURB T DROP(T-S)	87.79
6.FC TURB EXIT T(T)	396.63
7.OC TURB EXIT T(T)	427.36
8.DRIVE GAS GAMMA	1.391
9.DRIVE GAS CP	3.771

HORSEPOWERS
AND EFFICIENCIES

(FC=FUEL CIRCUIT)
(OC=OX CIRCUIT)
(T-S=TOTAL TO STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURB HORSEPOW	1477.62
2.OC TURB HORSEPOW	283.39
3.FUEL PUMP SHP	1477.62
4.OX PUMP SHP	283.39
5.FC TURB EFF	.756
6.OC TURB EFF	.806
7.FUEL PUMP EFF	.675
8.OX PUMP EFF	.658
9.TOTAL FUEL FLOW	6.03
10.TOTAL OX FLOW	36.15
11.TURBINE BYPASS FLOW	.36

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TABLE IV

SERIES TURBINES POWER BALANCE (F = 10K LB)

EXPANDER CYCLE:
SERIES TURBINES
NO REHEAT
BOOST PUMPS

PRESSURE SCHEDULE (PSIA)

	FUEL CIRCUIT	LOX CIRCUIT
1. PUMP INLET	51.00	46.00
2. PUMP PRESSURE RISE	2644.45	1561.43
3. PUMP DISCHARGE	2695.45	1608.03
4. LINE PRESSURE DROP	10.00	25.00
5. VALVE INLET	2685.45	1583.03
6. VALVE PRESSURE DROP	26.85	15.83
7. VALVE OUTLET	2658.59	1567.20
8. LINE PRESSURE DROP	30.00	15.00
9. COOLANT JACKET INLET	2628.59	--
10. COOLANT JACKET PRESSURE DROP	131.00	--
11. COOLANT JACKET OUTLET	2497.59	--
12. LINE PRESSURE DROP	30.00	--
13. FUEL CIRCUIT TURBINE INLET	2467.59	--
14. FUEL CIRCUIT TURBINE PRESSURE RAT.	1.54A	--
15. FUEL CIRCUIT TURBINE EXIT	1035.41	--
15A. BETWEEN TURBINES PRESSURE DROP	50.89	--
15B. OX CIRCUIT TURBINE INLET	1584.52	--
15C. OX CIRCUIT TURBINE PRESSURE RAT.	1.103	--
15D. OX CIRCUIT TURBINE EXIT	1474.97	--
16. LINE PRESSURE DROP	36.75	--
17. TCA INJECTOR INLET	1437.27	1552.20
18. TCA INJECTOR PRESSURE DROP	117.44	232.83
19. TCA INJECTOR FACE	1319.37	1319.37
20. TCA PRESSURE DROP	19.37	19.37
21. CHAMBER PRESSURE	1300.00	1300.00

FLOWRATES (LBM/SEC)
TEMP DRF (DEGREES R)
CP(BTU/LBM-R)
(FC=FUEL CIRCUIT)
(CC=OX CIRCUIT)
(T-S=TOTAL TC STATIC TEMP)
(T=TOTAL TEMP)

1. FC TURBINE FLOW	2.80	
2. OC TURBINE FLOW	2.80	
3. FC TURB T INLP(T-S)	75.95	
4. OC TURB T INLP(T-S)	16.35	
5. FC TURB INLET T(T)	653.00	
6. FC TURB EXIT T(T)	597.56	
7. OC TURB INLET T(T)	597.56	
8. OC TURB EXIT T(T)	585.13	
9. DRIVE GAS CP	3.530	
10. DRIVE GAS GAMMA	1.395	
11. BYPASS FLOW	.18	

HORSEPOWERS
AND EFFICIENCIES

(FC=FUEL CIRCUIT)
(CC=OX CIRCUIT)
(T-S=TOTAL TC STATIC TEMP)
(T=TOTAL TEMP)

1. FC TURB HORSEPOW	774.17	
2. OC TURB HORSEPOW	173.50	
3. FL PUMP SHP	774.17	
4. OX PUMP SHP	173.50	
5. FC TURB EFF	.730	
6. OC TURBINE EFF	.760	
7. FUEL PUMP EFF	.620	
8. OX PUMP EFF	.620	
9. OX FLOW	17.85	
10. TOTAL FUEL FLOW	2.97	

TABLE V

SERIES TURBINES POWER BALANCE (F = 15V LB)

EXPANDER CYCLE:
SERIES TURBINES
NO REHEAT
BOOST PUMPS

PRESSURE SCHEDULE (PSIA)

	FUEL CIRCUIT	LOX CIRCUIT
1.PUMP INLET	51.00	46.60
2.PUMP PRESSURE RISE	2422.32	1840.83
3.PUMP DISCHARGE	2473.32	1887.43
4.LINE PRESSURE DROP	10.00	25.00
5.VALVE INLET	2463.32	1862.43
6.VALVE PRESSURE DROP	24.63	14.62
7.VALVE OUTLET	2438.65	1847.80
8.LINE PRESSURE DROP	30.00	15.00
9.COOLANT JACKET INLET	2408.65	--
10.COOLANT JACKET PRESSURE DROP	92.50	--
11.COOLANT JACKET OUTLET	2316.05	--
12.LINE PRESSURE DROP	30.00	--
13.FUEL CIRCUIT TURBINE INLET	2286.05	--
14.FUEL CIRCUIT TURBINE PRESSURE RAT.	1.544	--
15.FUEL CIRCUIT TURBINE EXIT	1518.55	--
15A.BETWEEN TURBINES PRESSURE DROP	47.98	--
15B.OX CIRCUIT TURBINE INLET	1470.58	--
15C.OX CIRCUIT TURBINE PRESSURE RAT.	1.109	--
15D.OX CIRCUIT TURBINE EXIT	1360.78	--
16.LINE PRESSURE DROP	33.98	--
17.TCA INJECTOR INLET	1326.48	1432.80
18.TCA INJECTOR PRESSURE DROP	108.60	214.92
19.TCA INJECTOR FACE	1217.88	1217.88
20.TCA PRESSURE DROP	17.88	17.88
21.CHAMBER PRESSURE	1200.00	1200.00

FLOWRATES (LBM/SEC)
TEMP UPLF (DEGREES R)
CP(BTU/LBM-R)
(FC=FUEL CIRCUIT)
(LC=OX CIRCUIT)
(T-S=TOTAL TO STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURBINE FLOW	4.22
2.OC TURBINE FLOW	4.22
3.FC TURB T DROP(T-S)	61.96
4.OC TURB T DROP(T-S)	14.12
5.FC TURB INLET T(I)	535.00
6.FC TURB EXIT T(I)	488.53
7.OC TURB IN T(I)	488.53
8.OC TURB EXIT T(I)	477.73
9.DRIVE GAS CP	3.652
10.DRIVE GAS GAMMA	1.395
11.BYPASS FLOW	.27

HORSEPOWERS
AND EFFICIENCIES
(FC=FUEL CIRCUIT)
(OC=OX CIRCUIT)
(T-S=TOTAL TO STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURB HORSEPOW	1913.21
2.OC TURB HORSEPOW	235.57
3.FL PUMP SHP	1913.21
4.OX PUMP SHP	235.57
5.FC TURB EFF	.750
6.OC TURBINE EFF	.765
7.FUEL PUMP EFF	.655
8.OX PUMP EFF	.636
9.OX FLOW	26.98
10.TOTAL FUEL FLOW	4.49

TABLE VI

SERIES TURBINES POWER BALANCE (F = 20K LB)

EXPANDER CYCLE:
SERIES TURBINES
NO REHEAT
BOOST PUMPS

PRESSURE SCHEDULE (PSIA)

	FUEL CIRCUIT	LCX CIRCUIT
1.PUMP INLET	51.00	46.60
2.PUMP PRESSURE RISE	2173.96	1320.22
3.PUMP DISCHARGE	2224.96	1360.82
4.LINE PRESSURE DROP	10.00	25.00
5.VALVE INLET	2214.96	1341.82
6.VALVE PRESSURE DRCP	22.15	13.42
7.VALVE OUTLET	2192.81	1328.40
8.LINE PRESSURE DROP	30.00	15.00
9.COOLANT JACKET INLET	2162.81	--
10.COOLANT JACKET PRESSURE DROP	76.00	--
11.COOLANT JACKET OUTLET	2086.81	--
12.LINE PRESSURE DROP	30.00	--
13.FUEL CIRCUIT TURBINE INLET	2056.81	--
14.FUEL CIRCUIT TURBINE PRESSURE RAT.	1.514	--
15.FUEL CIRCUIT TURBINE EXIT	1393.77	--
15A.BETWEEN TURBINES PRESSURE DRCP	44.84	--
15B.OX CIRCUIT TURBINE INLET	1348.92	--
15C.OX CIRCUIT TURBINE PRESSURE RAT.	1.109	--
15D.OX CIRCUIT TURBINE EXIT	1247.68	--
16.LINE PRESSURE DROP	31.18	--
17.TCA INJECTOR INLET	1216.50	1313.40
18.TCA INJECTOR PRESSURE DROP	100.11	197.01
19.TCA INJECTOR FACE	1116.39	1116.39
20.TCA PRESSURE DRCP	16.39	16.39
21.CHAMBER PRESSURE	1100.00	1100.00

FLOWRATES (LBM/SEC)
TEMP DRGF (DEGREES R)
CP(BTU/LBM-R)
(FC=FUEL CIRCUIT)
(OC=OX CIRCUIT)
(T-S=TOTAL TO STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURBINE FLOW	5.66
2.OC TURBINE FLOW	5.66
3.FC TURB T DROP(T-S)	50.84
4.OC TURB T DROP(T-S)	12.18
5.FC TURB INLET T(T)	463.80
6.FC TURB EXIT T(T)	423.81
7.OC TURB IN T(T)	423.81
8.OC TURB EXIT T(T)	414.44
9.DRIVE GAS CP	3.771
10.DRIVE GAS GAMMA	1.391
11.BYPASS FLOW	.36

HORSEPOWERS
AND EFFICIENCIES

(FC=FUEL CIRCUIT)
(OC=OX CIRCUIT)
(T-S=TOTAL TO STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURB HORSEPOW	1183.95
2.OC TURB HORSEPOW	283.39
3.FL PUMP SHP	1183.95
4.OX PUMP SHP	283.39
5.FC TURB EFF	.778
6.OC TURBINE EFF	.778
7.FUEL PUMP EFF	.675
8.OX PUMP EFF	.650
9.OX FLOW	36.15
10.TOTAL FUEL FLOW	6.03

II, B, Cycle Optimization (cont.)

Thrust, K lb	Cycle	Fuel Pump Discharge Pressure, PSIA	Chamber Pressure, PSIA	Engine Specific Impulse, Sec	Nozzle Area Ratio
10	Parallel Turbines	3545	1300	480.2	792
15		3174	1200	477.2	473
20		2764	1100	474.2	322
10	Series Turbines	3545	1480	481.2	900
15		3174	1345	478.1	530
20		2764	1225	475.1	360

The data show that the performance gains are small (about 1 sec) because the rate of change in specific impulse with area ratio decreases as area ratio increases. This can be seen from Figure 21. The effect of the operating chamber pressure on engine weight is negligible over a small range as discussed in Section II, C. of this report.

Based upon this analysis, it would appear to be more desirable to accept a lower chamber pressure with a small decrease in specific impulse ($\leq$ 1 sec). This would increase the cycle power balance margin and provide a contingency that may be required during the engine development program.

2.   Turbine Exhaust Heat Regeneration Cycle Analysis

The objective of this portion of the study was to evaluate the use of a turbine exhaust gas regenerator in the expander cycle engine and to identify optimized operating conditions. Regenerator performance for 10,000, 15,000 and 20,000 pounds thrust was evaluated with emphasis placed

Figure 21. O_2/H_2 ODE Performance, MR = 6.0

II, B, Cycle Optimization (cont.)

upon the series turbine engine configuration which was selected on the basis of the results presented in Paragraph II, B,1.

The regenerator concept employs a heat exchanger to transfer energy from the turbine exhaust gas to the liquid hydrogen discharging from the pump prior to entering the combustion chamber coolant jacket. From the regenerator, the turbine exhaust gas enters the injector. The heated hydrogen enters the cooling passageways of the thrust chamber jacket and nozzle and then drives the turbines. A simplified engine cycle schematic is shown on Figure 22.

Utilizing a turbine exhaust gas regenerator in the expander cycle results in an increased heat flow to the hydrogen and thus, a higher turbine inlet temperature. This can result in more turbine horsepower output, higher chamber pressure, or in more turbine bypass and/or cycle margin if desired. The full benefit of the increased heat flow is offset partly by a simultaneous increase in system pressure losses. A parametric study was conducted to optimize the engine performance and identify regenerator operating conditions. Pertinent details are included in the following discussion.

a. Regenerative Chamber

The use of the regenerator results in an increased hydrogen coolant inlet temperature to the regenerative chamber liner. The effect of this is an increase in the pressure losses through the chamber liner for the same chamber heat flow. Figure 23 depicts the relationships for 10K, 15K and 20K thrust levels. The regenerator outlet temperature (for the hydrogen coolant) and the jacket coolant inlet temperature are assumed to be the same in this analysis.

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P = PUMP
T = TURBINE
HX = HEAT EXCHANGER
1 = LH2 SHUTOFF VALVE
2 = LOX SHUTOFF VALVE
3 = TURBINE BYPASS VALVE
4 = TURBINE FLOW CONTROL VALVE
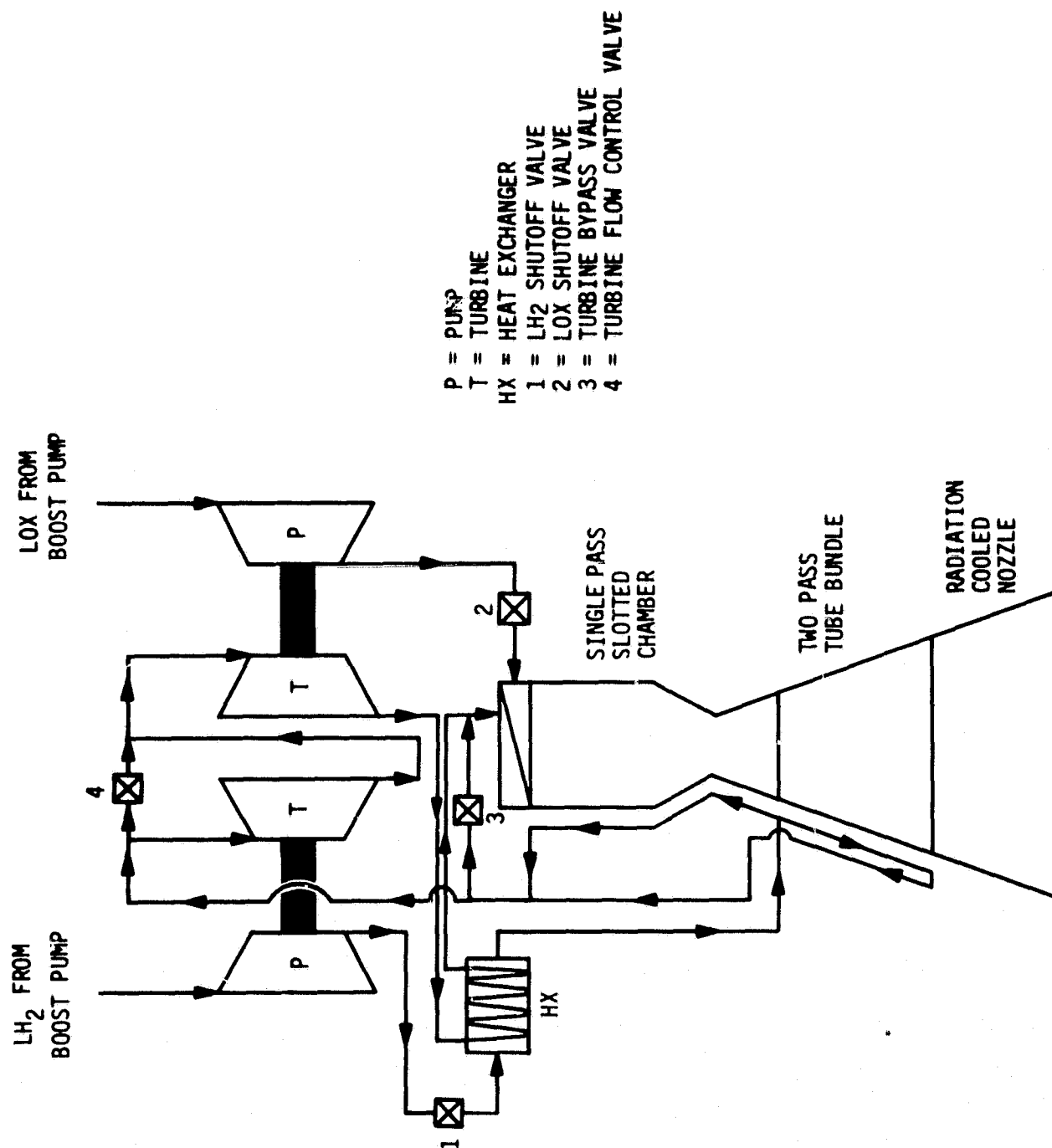
Figure 22.   Turbine Exhaust Heat Regeneration, Series Turbines, Advanced Expander Cycle Flow Schematic
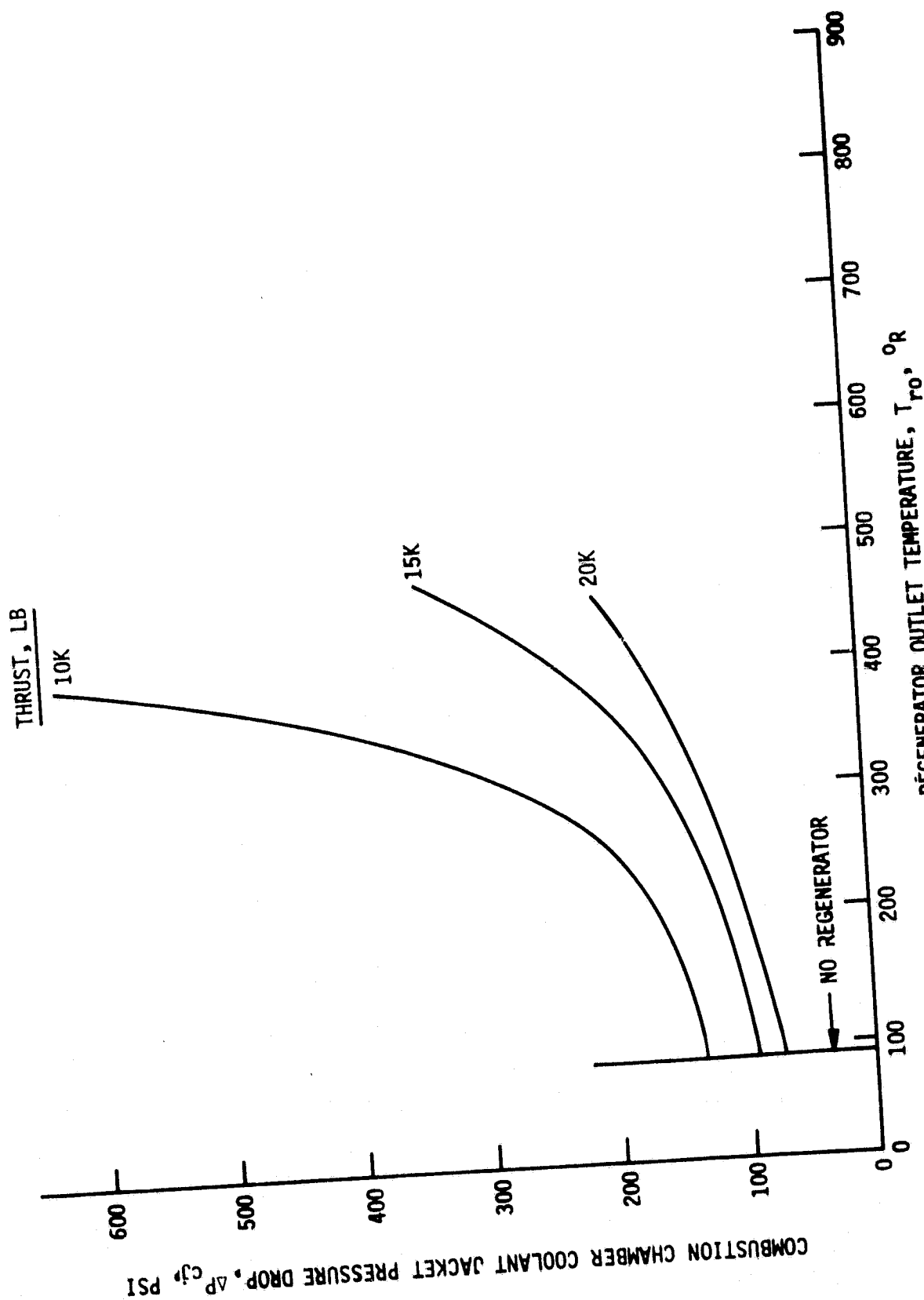
Figure 23. Effect of Increased Jacket Inlet Temperature on Jacket Pressure Losses

II, B, Cycle Optimization (cont.)

b.   Engine Cycle Power Balance

Utilizing the total heat flow to the coolant to deter-
mine turbine inlet temperature and the aforementioned jacket pressure loss
relationships, engine cycle power balances were predicted for various regenera-
tor performance levels.

The series turbine engine performance and power balance
model was used for each thrust level, and at the respective baseline configura-
tions. The baseline parameters at each thrust level are presented in the
table below.

			THRUST, LB	
	PARAMETER	10,000	15,000	20,000
Chamber Pressure	Pc, psia	1300	1200	1100
Fuel Flowrate	$\dot{w}_{fuel}$, lb/sec	3.0	4.5	6.0
Engine Mixture Ratio	MR	6.0	6.0	6.0
Chamber Length	L', inches	18	18	18
Chamber Contraction Ratio	C_R	3.66	3.66	3.66
Ox Pump Efficiency	η_{po}	.620	.636	.650
Fuel Pump Efficiency	η_{pf}	.620	.655	.675
Ox Turbine Efficiency	η_{to}	.760	.765	.770
Fuel Turbine Efficiency	η_{tf}	.730	.750	.770

Pressure losses through the regenerator, both the cold circuit and hot gas cir-
cuit, were varied from 50 psia to 200 psia to determine their effect and
sensitivity.

Because the previous analysis showed only minor performance
variations with chamber pressure, the approach in this subtask was to hold chamber
pressure constant. However, the chamber pressure and performance potential are
also addressed.

II, B, Cycle Optimization (cont.)

The major engine operating parameters of interest
for the constant chamber pressure cases are the fuel (hydrogen) pump dis-
charge pressure and turbine pressure ratio. These parameters provide the
insight to the cycle sensitivity to component variations. For a given thrust
and flowrate, a minimum discharge pressure and pressure ratio is desirable.
For ease of comparison, an overall pressure ratio, across both fuel and
oxidizer turbines, was used with the series turbine analysis.

Figure 24 graphically presents the results of the engine
power balance data. From this figure, the optimum regenerator outlet tempera-
tures were selected as:

THRUST, lbs	REGENERATOR OUTLET TEMPERATURE, °R
10,000	310
15,000	380
20,000	500

As discussed, the regenerator pressure losses were varied
to determine the effect on the engine power balance. From the results shown
in Figure 25, it can be concluded that 1) the fuel pump discharge pressure
and turbine pressure ratio are obviously reduced by decreasing the regenerator
pressure losses, and 2) the selection of the optimized regenerator outlet
temperature is not significantly affected by the level of regenerator pressure
losses.

c.   Regenerator Characteristics

From previous studies (in-house IR&D), it was determined
that a platelet type heat exchanger would be able to provide the large amount
of heat transfer surface area with a minimum packaging size. Many, small
passageways would be used to pass the fluids.

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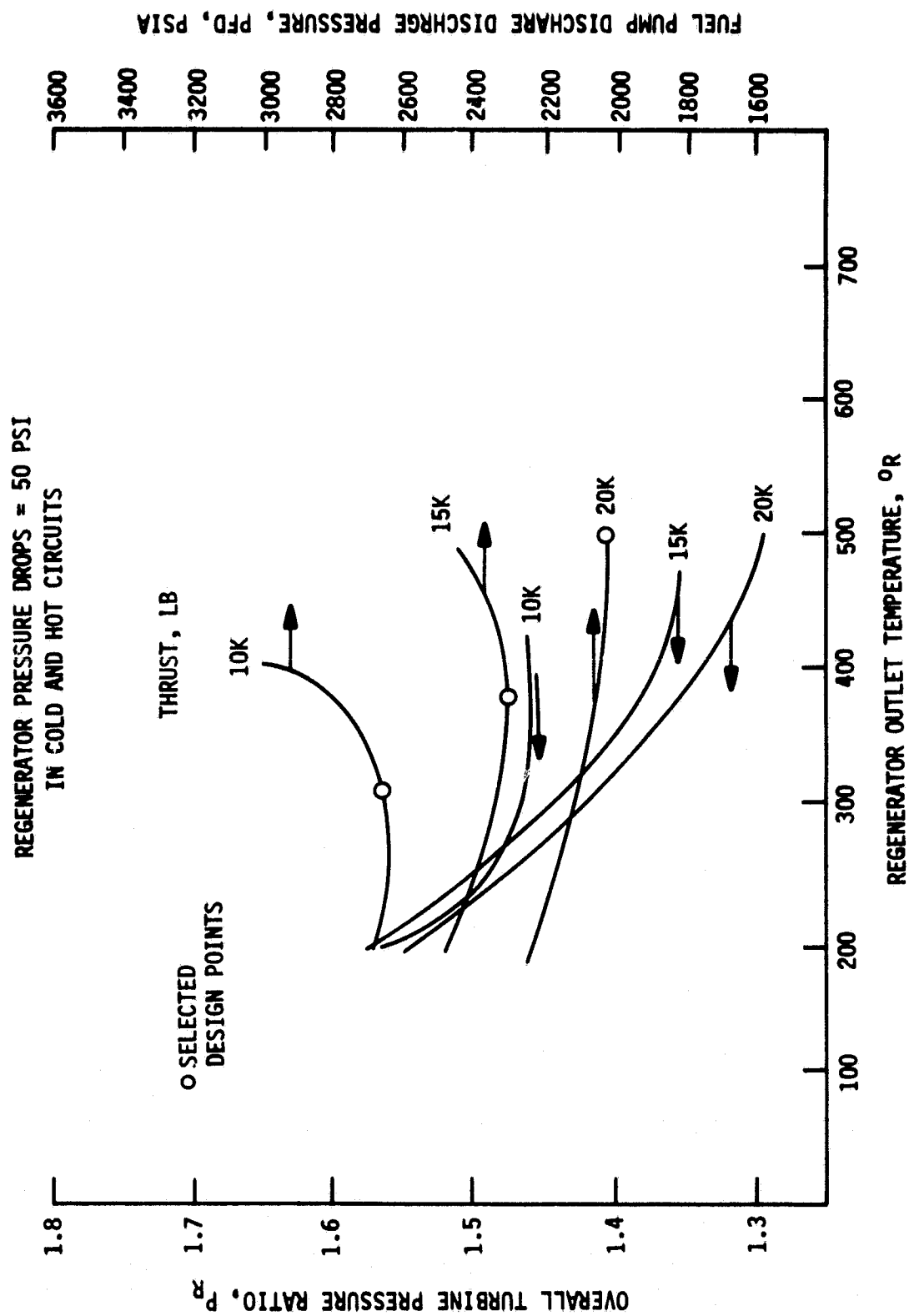
Figure 24. Engine Power Balance Data versus Regenerator Outlet Temperature
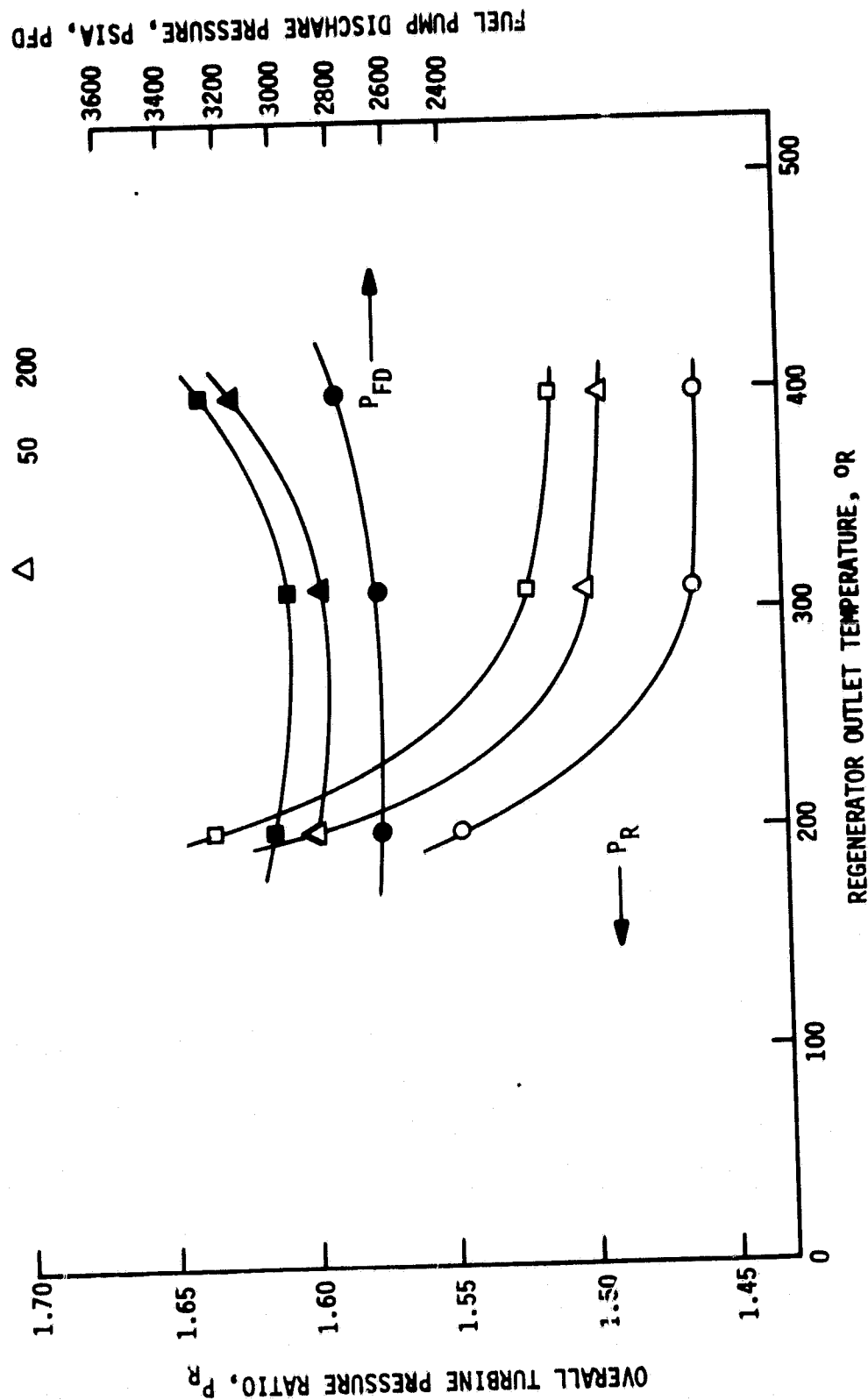
Figure 25. Effect of Regenerator Pressure Losses on Engine Power Balance

II, B, Cycle Optimization (cont.)

The inlet conditions and the selected cold circuit
outlet temperature determined the gas outlet temperature. The turbine exhaust
gas temperature at the regenerator inlet was estimated from preliminary
engine cycle power balances. The regenerator inlet and outlet temperatures
are shown below.

TEMPERATURE, °R

THRUST	COLD IN	COLD OUT	HOT IN	HOT OUT
10K	90	310	750	510
15K	90	380	780	490
20K	90	500	860	425

The cold circuit inlet and hot gas inlet pressures
utilized for estimating fluid properties were 3000 psi and 1500 psi, respec-
tively, for all thrust levels. A deviation from these values does not signi-
ficantly affect the results of these preliminary studies.

A steady state heat transfer model, developed during an
ALRC IR&D study, was used to estimate the size, weight, and pressure drop
relationships for a counterflow heat exchanger core. The independent variable
in determining these relationships is the number of channels, or since the
channel geometry is fixed, the frontal area.

The regenerator pressure losses were assumed to be twice
the predicted core frictional and inlet/outlet pressure losses. The weight

II, B, Cycle Optimization (cont.)

of the 10K regenerator was estimated as twice the core weight. Scaling, based on the number of channels, the weights of the 15K and 20K regenerators were estimated to be 1.5 times and 1.3 times the core weight, respectively. Figures 26, 27 and 28 present the results of the heat exchanger modeling.

From the appropriate curves, regenerator design points (weight, pressure losses) were selected and are shown below. The considerations in selecting these points were minimum weight in a region of lesser sensitivity of pressure drop to weight fluctuations (as a result of operation or design changes).

| | THRUST lbs | | |
	10,000	15,000	20,000
Temp, hot in (°R)	750	780	860
Temp, hot out (°R)	510	490	425
Temp, cold in (°R)	90	90	90
Temp, cold out (°R)	310	380	500
ΔP (cold circuit) (psi)	35	60	60
ΔP (hot circuit) (psi)	35	40	25
Weight (lbs)	36	60	133
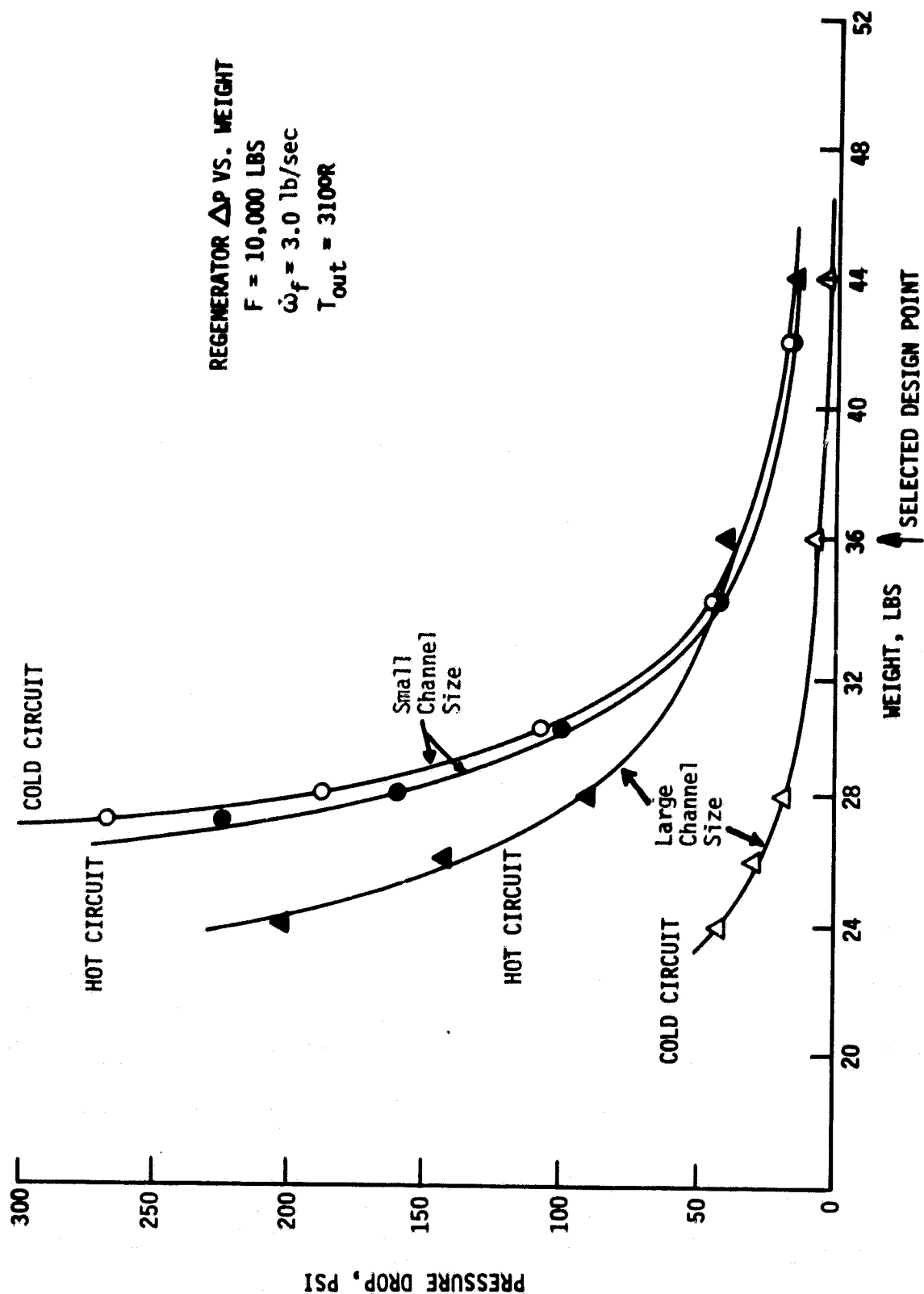
Figure 26. 10K Regenerator Weight-Pressure Loss Relationships

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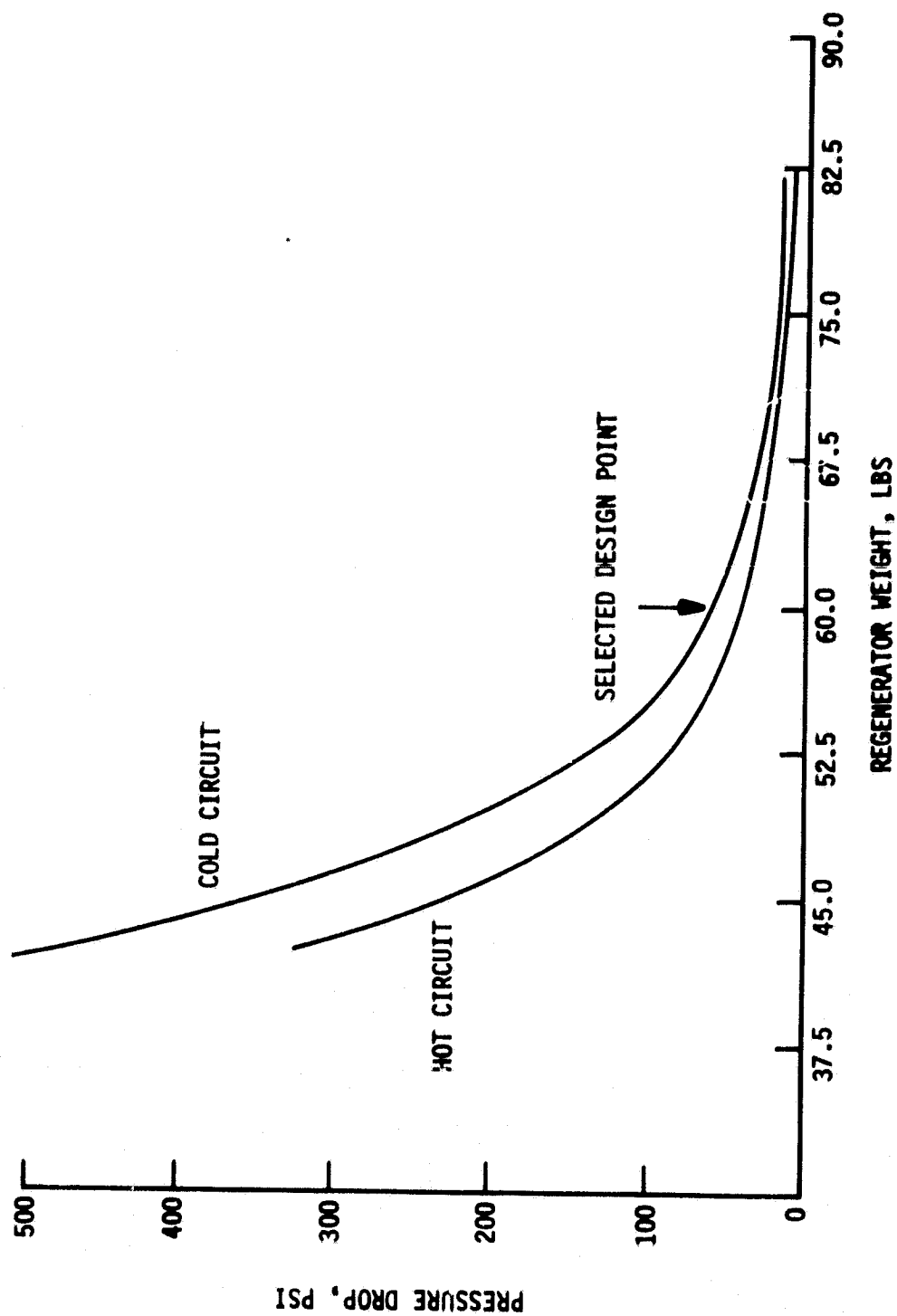
Figure 27.   15K Regenerator Weight-Pressure Loss Relationships
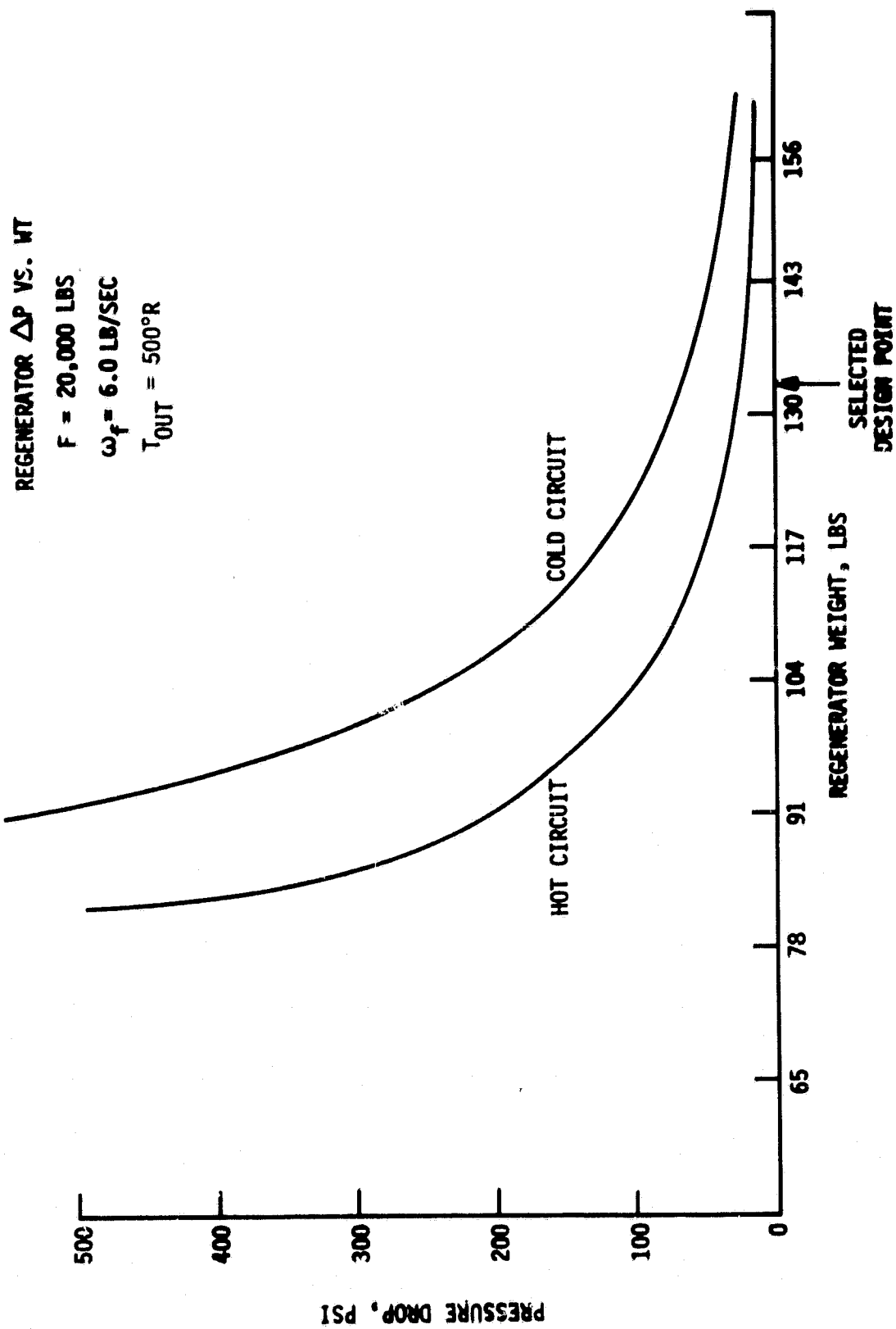
Figure 28. 20K Regenerator Weight-Pressure Loss Relationships

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II, B, Cycle Optimization (cont.)

The drastic increase in weight for the 20K regenerator from the 10K regenerator results from the high heat flow required to increase the large fuel flow (6.0 lb/sec.) to the high temperature (500°R). The 500°F point was selected disregarding weight. Reducing the temperature output level will reduce the weight, with a small increase in fuel pump discharge pressure and also an increase in turbine pressure ratio. However, a regenerator weight of about 95 lbs is about the minimum and pressure drop gets excessive.

d.   Cycle Comparisons

Engine power balance calculations at or very near the optimum selected conditions for the series turbines, turbine exhaust heat regeneration cycles are shown on Tables VII, VIII and IX. These results are compared to the series turbines (without a regenerator) cycles below for fixed chamber pressures at each thrust level which results in equal performance engines.

Thrust, lb	Chamber Pressure PSIA	Series Turbines Cycle	Turbine Exhaust Heat Regeneration, Series Turbines Cycle
10,000	1300	2695	2645
15,000	1200	2473	2331
20,000	1100	2225	2036

The above comparisons show that the regenerator pays off more as the thrust is increased. This occurs because the baseline higher thrust cases have lower turbine inlet temperatures and more enhancement is possible. The comparison also shows that for these cases, the gains with a regenerator are modest. Therefore, the value of adding an engine component and increasing the system complexity and weight is questionable. The addition of a regenerator is probably best held as a design backup if needed.

TABLE VII

TURBINE EXHAUST HEAT REGENERATION, SERIES TURBINES, POWER BALANCE (F = 10K lb)

POWER BALANCE
EXPANDER CYCLE:
SERIES TURBINES
TURBINE EXHAUST HEAT REGENERATION
BOOST PUMPS

PRESSURE SCHEDULE (PSIA)

	FUEL CIRCUIT	LOX CIRCUIT
1.PUMP INLET	51.00	46.60
2.PUMP PRESSURE RISE	2594.07	1561.43
3.PUMP DISCHARGE	2645.07	1608.03
4.LINE PRESSURE DROP	10.00	25.00
5.VALVE INLET	2035.07	1583.03
6.VALVE PRESSURE DROP	20.35	15.83
7.VALVE OUTLET	2606.72	1567.20
8.LINE PRESSURE DROP	13.50	15.00
8A.HEAT EXCHANGER INLET	2590.72	--
8B.HEAT EXCHANGER PRESSURE DROP	50.00	--
8C.HEAT EXCHANGER DISCHARGE	2548.72	--
8D.LINE PRESSURE DROP	30.00	--
9.COOLANT JACKET INLET	2516.72	--
10.COOLANT JACKET PRESSURE DROP	285.00	--
11.COOLANT JACKET OUTLET	2233.72	--
12.LINE PRESSURE DROP	30.00	--
13.FUEL CIRCUIT TURBINE INLET	2203.72	--
14.FUEL CIRCUIT TURBINE PRESSURE RAT.	1.350	--
15A.FUEL CIRCUIT TURBINE EXIT	1000.96	--
15B.BETWEEN TURBINES PRESS.PL DROP	51.67	--
15C.OX CIRCUIT TURBINE INLET	1015.24	--
15D.OX CIRCUIT TURBINE PRESSURE RAT.	1.75	--
15E.OX CIRCUIT TURBINE EXIT	1560.18	--
16.LINE PRESSURE DROP	36.65	--
16A.HEAT EXCHANGER INLET	1547.51	--
16B.HEAT EXCHANGER PRESSURE DROP	50.00	--
16C.HEAT EXCHANGER DISCHARGE	1457.51	--
16D.LINE PRESSURE DROP	14.33	--
17.TCA INJECTOR INLET	1436.18	1552.26
18.TCA INJECTOR PRESSURE DROP	112.81	232.83
19.TCA INJECTOR FACE	1319.37	1519.37
20.TCA PRESSURE DROP	19.37	19.37
21.CHAMBER PRESSURE	1300.00	1300.00

FLOWRATES (LBM/SEC)
TEMP DROP (DEGREES R)
CP (BTU/LBM-R)
(FC=FUEL CIRCUIT)
(OC=OX CIRCUIT)
(T-S=TOTAL TC STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURBINE FLOW	2.80
2.OC TURBINE FLOW	2.80
3.FC TURB T DROP(T-S)	74.50
4.OC TURB T DROP(T-S)	16.35
5.FC TURB INLET T(T)	902.00
6.FC TURB EXIT T(T)	847.61
7.OC TURB INLET T(T)	847.61
8.OC TURB EXIT T(T)	835.19
9.DRIVE GAS CP	3.530
10.DRIVE GAS GAMMA	1.395

HORSEPOWERS AND EFFICIENCIES
(FC=FUEL CIRCUIT)
(OC=OX CIRCUIT)
(T-S=TOTAL TO STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURB HORSEPOW	759.92
2.OC TURB HORSEPOW	173.50
3.FC PUMP SHP	759.92
4.OX PUMP SHP	173.50
5.FC TURBINE EFF	.730
6.OC TURBINE EFF	.760
7.FUEL PUMP EFF	.620
8.OX PUMP EFF	.620
9.OX FLC	17.85
10.TOTAL FUEL FLO	2.97
11.TURBINE BYPASS FLOW	.18

TABLE VIII

TURBINE EXHAUST HEAT REGENERATION, SERIES TURBINES, POWER BALANCE (F = 15K lb)

POWER BALANCE
EXPANDER CYCLE:
SERIES TURBINES
TURBINE EXHAUST HEAT REGENERATION
BOOST PUMPS

PRESSURE SCHEDULE (PSIA)

	FUEL CIRCUIT	LOX CIRCUIT
1.PUMP INLET	51.00	46.60
2.PUMP PRESSURE RISE	2279.59	1440.83
3.PUMP DISCHARGE	2330.59	1487.43
4.LINE PRESSURE DROP	10.00	25.00
5.VALVE INLET	2320.59	1462.43
6.VALVE PRESSURE DROP	23.21	14.02
7.VALVE OUTLET	2297.38	1447.80
8.LINE PRESSURE DROP	10.00	15.00
8A.HEAT EXCHANGER INLET	2287.38	---
8B.HEAT EXCHANGER PRESSURE DROP	50.00	---
8C.HEAT EXCHANGER DISCHARGE	2237.38	---
8D.LINE PRESSURE DROP	30.00	---
9.COOLANT JACKET INLET	2207.38	---
10.COOLANT JACKET PRESSURE DROP	158.00	---
11.COOLANT JACKET OUTLET	2049.38	---
12.LINE PRESSURE DROP	30.00	---
13.FUEL CIRCUIT TURBINE INLET	2019.38	---
14.FUEL CIRCUIT TURBINE PRESSURE RAT.	1.317	---
15.FUEL CIRCUIT TURBINE EXIT	1549.0?	---
15A.BETWEEN TURBINES PRESSURE DROP	48.71	---
15B.OX CIRCUIT TURBINE INLET	1500.35	---
15C.OX CIRCUIT TURBINE PRESSURE RAT.	1.075	---
15D.OX CIRCUIT TURBINE EXIT	1431.60	---
16.LINE PRESSURE DROP	35.75	---
16A.HEAT EXCHANGER INLET	1395.81	---
16B.HEAT EXCHANGER PRESSURE DROP	50.00	---
16C.HEAT EXCHANGER DISCHARGE	1345.81	---
16D.LINE PRESSURE DROP	17.85	---
17.TCA INJECTOR INLET	1327.91	1032.80
18.TCA INJECTOR PRESSURE DROP	110.03	214.92
19.TCA INJECTOR FACE	1217.88	1217.88
20.TCA PRESSURE DROP	17.88	17.88
21.CHAMBER PRESSURE	1200.00	1200.00

FLOWRATES (LBM/SEC)
TEMP DROP (DEGREES R)
CP(BTU/LBM-R)
(FC=FUEL CIRCUIT)
(OC=OX CIRCUIT)
(T-S=TOTAL TO STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURBINE FLOW	4.22
2.OC TURBINE FLOW	4.22
3.FC TURB T DRCP(T-S)	60.32
4.OC TURB T DRCP(T-S)	14.01
5.FC TURB INLET T(T)	764.00
6.FC TURB EXIT T(T)	718.76
7.OC TURB INLET T(T)	718.76
8.OC TURB EXIT T(T)	707.58
9.DRIVE GAS CP	3.530
10.DRIVE GAS GAMMA	1.395

HORSEPOWERS
AND EFFICIENCIES
(FC=FUEL CIRCUIT)
(OC=OX CIRCUIT)
(T-S=TOTAL TO STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURB HORSEPOW	953.50
2.OC TURB HORSEPOW	235.57
3.FC PUMP SHP	953.50
4.OX PUMP SHP	235.57
5.FC TURBINE EFF	.750
6.OC TURBINE EFF	.765
7.FUEL PUMP EFF	.655
8.OX PUMP EFF	.636
9.OX FLOW	26.94
10.TOTAL FUEL FLO	4.40
11.TURBINE BYPASS FLOW	.27

TABLE IX

TURBINE EXHAUST HEAT REGENERATION, SERIES TURBINES, POWER BALANCE (F = 20K lb)

POWER BALANCE
EXPANDER CYCLE
SERIES TURBINES
TURBINE EXHAUST HEAT REGENERATION
BOOST PUMPS

PRESSURE SCHEDULE (PSIA)

	FUEL CIRCUIT	LOX CIRCUIT
1.PUMP INLET	51.00	46.00
2.PUMP PRESSURE RISE	1985.04	1320.22
3.PUMP DISCHARGE	2036.04	1366.82
4.LINE PRESSURE DROP	10.00	25.00
5.VALVE INLET	2026.04	1341.82
6.VALVE PRESSURE DROP	20.26	13.42
7.VALVE OUTLET	2005.78	1328.40
8.LINE PRESSURE DROP	10.00	15.00
8A.HEAT EXCHANGER INLET	1995.78	--
8B.HEAT EXCHANGER PRESSURE DRCP	50.00	--
8C.HEAT EXCHANGER DISCHARGE	1945.78	--
8D.LINE PRESSURE DROP	30.00	--
9.COOLANT JACKET INLET	1915.78	--
10.COOLANT JACKET PRESSURE DROP	200.00	--
11.COOLANT JACKET OUTLET	1715.78	--
12.LINE PRESSURE DROP	30.00	--
13.FUEL CIRCUIT TURBINE INLET	1685.78	--
14.FUEL CIRCUIT TURBINE PRESSURE RAT.	1.233	--
15.FUEL CIRCUIT TURBINE EXIT	1402.58	--
15A.BETWEEN TURBINES PRESSURE DRCP	45.06	--
15B.OX CIRCUIT TURBINE INLET	1357.51	--
15C.OX CIRCUIT TURBINE PRESSURE RAT.	1.058	--
15D.OX CIRCUIT TURBINE EXIT	1316.55	--
16.LINE PRESSURE DROP	32.91	--
16A.HEAT EXCHANGER INLET	1283.67	--
16B.HEAT EXCHANGER PRESSURE DRCP	50.00	--
16C.HEAT EXCHANGER DISCHARGE	1233.67	--
16D.LINE PRESSURE DROP	16.46	--
17.TCA INJECTOR INLET	1217.22	1313.40
18.TCA INJECTOR PRESSURE DROP	100.83	167.01
19.TCA INJECTOR FACE	1116.39	1116.39
20.TCA PRESSURE DRCP	16.39	16.39
21.CHAMBER PRESSURE	1100.00	1100.00

FLOWRATES (LBM/SEC)
TEMP DROP (DEGREES R)
CP(BTU/LB-R)
(FC=FUEL CIRCUIT)
(OC=OX CIRCUIT)
(T-S=TOTAL TO STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURBINE FLOW	5.66
2.OC TURBINE FLOW	5.66
3.FC TURB T DROP(T-S)	45.64
4.OC TURB T DROP(T-S)	13.01
5.FC TURB INLET T(T)	863.00
6.FC TURB EXIT T(T)	824.77
7.OC TURB INLET T(T)	824.77
8.OC TURB EXIT T(T)	814.75
9.DRIVE GAS CP	3.530
10.DRIVE GAS GAMMA	1.395

HORSEPOWERS
AND EFFICIENCIES

(FC=FUEL CIRCUIT)
(OC=OX CIRCUIT)
(T-S=TOTAL TO STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURB HORSEPOW	1081.06
2.OC TURB HORSEPOW	283.39
3.FC PUMP SHP	1081.06
4.OX PUMP SHP	283.39
5.FC TURBINE EFF	.770
6.OC TURBINE EFF	.770
7.FUEL PUMP EFF	.675
8.OX PUMP EFF	.650
9.OX FLOW	36.15
10.TOTAL FUEL FLO	6.03
11.TURBINE BYPASS FLOW	.36

II, B, Cycle Optimization (cont.)

Comparisons were also made on the basis of system performance. For this analysis, the fuel pump discharge pressures at each thrust level were fixed at the series turbines values. Engine performance and weight trades were then performed. The results of this analysis are presented on Table X. The table shows that the turbine exhaust heat regeneration concept does not payoff on a payload basis. Performance increases are not large enough to compensate for the weight increases.

Because a parallel turbine drive cycle has been shown to be more sensitive then the series turbines, some analysis was conducted to show the affect of a regenerator on this cycle. Figure 29 is a simplified schematic of the parallel turbine, turbine exhaust heat regenerator cycle. A power balance at 10K lb thrust is shown on Table XI for 1300 psia chamber pressure. The fuel pump discharge pressure is 2936 psia compared to 3545 psia without a regenerator. This is a 609 psi reduction in the discharge pressure requirement. This converts to a 130 psia gain in thrust chamber pressure if the fuel pump discharge pressure is held constant. This chamber pressure gain would represent a 0.7 sec gain in specific impulse. The AMOTV performance/weight trade follows:

$$\Delta W_{PL} = \frac{\Delta W_{PL}}{\Delta I_s} \quad X \ \Delta \ I_s = +73 \ \frac{LB}{SEC} \quad X \ .7 \ SEC = +51.1 \ LB$$

$$\Delta W_{PL} = \frac{\Delta W_{PL}}{\Delta W_{eng}} \quad X \ \Delta W_{eng} = -1.1 \ \frac{LB}{LB} \ X \ 36 \ LB = -39.6 \ LB$$

$$TOTAL \quad \Delta W_{PL} = +11.5 \ LB$$

For this case, the addition of a regenerator shows a small gain. However, for the same case (i.e., P_{FD} = 3545, F = 10K LB), the series turbine arrangement, without a regenerator, has a 1 sec performance gain or a relative payload of +73 LB. This is a net payload advantage of 61.5 lbs when compared to the above example.

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TABLE X

SERIES TURBINES-TURBINE EXHAUST HEAT REGENERATION
PERFORMANCE/WEIGHT TRADES

THRUST, KLB	CYCLE	FUEL PUMP DISCHARGE PRESSURE, PSIA	CHAMBER PRESSURE, PSIA	NOZZLE AREA RATIO	ENGINE SPECIFIC IMPULSE, SEC	ENGINE[1] WEIGHT CHANGE, LB	CHANGE IN AMOTV PAYLOAD, LB
10	Series Turbines	2695	1300	792	480.2	0	----
10	Turbine Exhaust Heat Regeneration	2695	1311	800	480.3	36	-32
15	Series Turbines	2473	1200	473	477.2	0	----
15	Turbine Exhaust Heat Regeneration	2473	1230	485	477.4	60	-54
20	Series Turbines	2225	1100	322	474.2	0	----
20	Turbine Exhaust Heat Regeneration	2225	1145	335	474.6	133	-117

(1) Series Turbines Used as the Base in all Cases

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P = PUMP
T = TURBINE
HX = HEAT EXCHANGER
1 = LH2 SHUTOFF VALVE
2 = LOX SHUTOFF VALVE
3 = TURBINE BYPASS VALVE
4 = TURBINE FLOW CONTROL VALVE

LOX FROM
BOOST PUMP

LH$_2$ FROM
BOOST PUMP

SINGLE PASS
SLOTTED
CHAMBER

TWO PASS
TUBE BUNDLE

RADIATION
COOLED
NOZZLE

Figure 29. Turbine Exhaust Heat Regeneration, Parallel Turbines, Advanced
Expander Cycle Flow Schematic

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TABLE XI

TURBINE EXHAUST HEAT REGENERATION, PARALLEL TURBINES, POWER BALANCE (F = 10K lb)

POWER BALANCE
EXPANDER CYCLE
PARALLEL TURBINES
TURBINE EXHAUST REGENERATION
BOOST PUMPS

PRESSURE SCHEDULE (PSIA)

	FUEL CIRCUIT	LOX CIRCUIT
1.PUMP INLET	51.00	46.00
2.PUMP PRESSURE RISE	2885.13	1561.43
3.PUMP DISCHARGE	2936.13	1608.03
4.LINE PRESSURE DROP	10.00	25.00
5.VALVE INLET	2926.13	1583.03
6.VALVE PRESSURE DROP	29.26	15.83
7.VALVE INLET	2896.87	1567.20
8.LINE PRESSURE DROP	10.00	15.00
8A.HEAT EXCHANGER INLET	2886.87	---
8B.HEAT EXCHANGER PRESSURE DROP	50.00	---
8C.HEAT EXCHANGER EXIT	2836.87	---
8D.LINE PRESSURE DROP	36.00	---
9.COOLANT JACKET INLET	2808.87	---
10.COOLANT JACKET PRESSURE DROP	285.00	---
11.COOLANT JACKET OUTLET	2521.87	---
12.LINE PRESSURE DROP	20.00	---
12A.SPLITTER VALVE INLET	2501.87	---
12B.SPLITTER VALVE PRESSURE DROP	25.02	---
12C.SPLITTER VALVE EXIT	2476.85	---
12D.LINE PRESSURE DROP	10.00	---
13.TURBINE INLET	2466.85	---
14.TURBINE PRESSURE RATIO(DIS/DISCH)	1.62	---
15.TURBINE OUTLET	1562.21	---
16.LINE PRESSURE DROP	39.06	---
16A.HEAT EXCHANGER INLET	1523.15	---
16B.HEAT EXCHANGER(TURBINE EXHAUST)	50.00	---
16C.HEAT EXCHANGER EXIT	1473.15	---
16D.LINE PRESSURE DROP	39.06	---
17.TCA INJECTOR INLET	1434.10	1552.20
18.TCA INJECTOR PRESSURE DROP	114.73	232.83
19.TCA INJECTOR FACE	1319.37	1319.37
20.TCA PRESSURE DROP	19.37	19.37
21.CHAMBER PRESSURE	1300.00	1300.00

FLOWRATES (LBM/SEC)
TEMP DROP (DEGREES R)
CP(BTU/LBM-R)
(FC=FUEL CIRCUIT)
(GC=GX CIRCUIT)
(T-S=TOTAL TC STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURBINE FLOW	2.05
2.OC TURBINE FLOW	.78
3.FC TURB T DROP(T-S)	114.34
4.OC TURB T DROP(T-S)	114.34
5.TURB INLET T(T)	895.00
6.FC TURB EXIT T(T)	814.96
7.OC TURB EXIT T(T)	849.95
8.DRIVE GAS GAMMA	1.395
9.DRIVE GAS CP	3.530

HORSEPOWERS
AND EFFICIENCIES

(FC=FUEL CIRCUIT)
(GC=GX CIRCUIT)
(T-S=TOTAL TC STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURB HORSEPOWER	818.02
2.OC TURB HORSEPOWER	175.35
3.FL PUMP SHP	818.02
4.OX PUMP SHP	175.35
5.FC TURBINE EFF	.700
6.OC TURB EFF	.394
7.FUEL PUMP EFF	.647
8.OX PUMP EFF	.620
9.TOTAL OX FLO	16.04
10.TOTAL FL FLO	3.01
11.TURB BYPASS FLOW	.18

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II, B, Cycle Optimization (cont.)

3. Turbine Exhaust Gas Reheat Cycle Analysis

A simplified schematic of the turbine exhaust gas reheat cycle is shown on Figure 30. In this cycle, the hydrogen flow is first used to cool the combustion chamber and then drives the low horsepower oxidizer turbopump. The low horsepower pump is driven first to take only a small pressure and temperature drop across the turbine. The hydrogen flow is then used to cool the fixed portion of the nozzle before driving the high horsepower hydrogen pump. Six percent of the hydrogen flow again by-passes the turbines. Therefore, the fixed nozzle is cooled with 94 percent of the hydrogen flow.

Thermal analyses were conducted to support this analysis using the selected baseline chamber geometry. Chamber designs, previously discussed, were cooled with 85% of the hydrogen flow. In this case it is possible to cool with 100% of the hydrogen flow. This results in a small pressure drop increase as shown on Table XII.

Two-pass A-286 tube bundles were designed to cool the nozzle from area ratio 8:1 to the end of the fixed nozzle section. All designs are based on round tubes with a linearly tapered wall thickness. Wall thicknesses at each end were selected to meet wall strength criteria; however, the forward end wall thickness was not allowed to be less than 0.007 in. For each thrust level, the number of tubes was varied in order to define a design with wall temperatures consistent with the cycle life criteria. The resultant number of tubes, pressure drop and hydrogen outlet temperature are shown on Table XII. Temperature rises obtained in the nozzle are significant while the pressure drops are small. The nozzle coolant inlet temperatures and pressures were calculated from preliminary cycle power balances and used as input to the thermal analysis.

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LOX FROM
BOOST PUMP

LH$_2$ FROM
BOOST PUMP

P = PUMP
T = TURBINE
1 = LH2 SHUTOFF VALVE
2 = LOX SHUTOFF VALVE
3 = TURBINE BYPASS VALVE
4 = TURBINE FLOW CONTROL VALVE

SINGLE
PASS
SLOTTED
CHAMBER

TWO PASS
TUBE BUNDLE

RADIATION
COOLED
NOZZLE
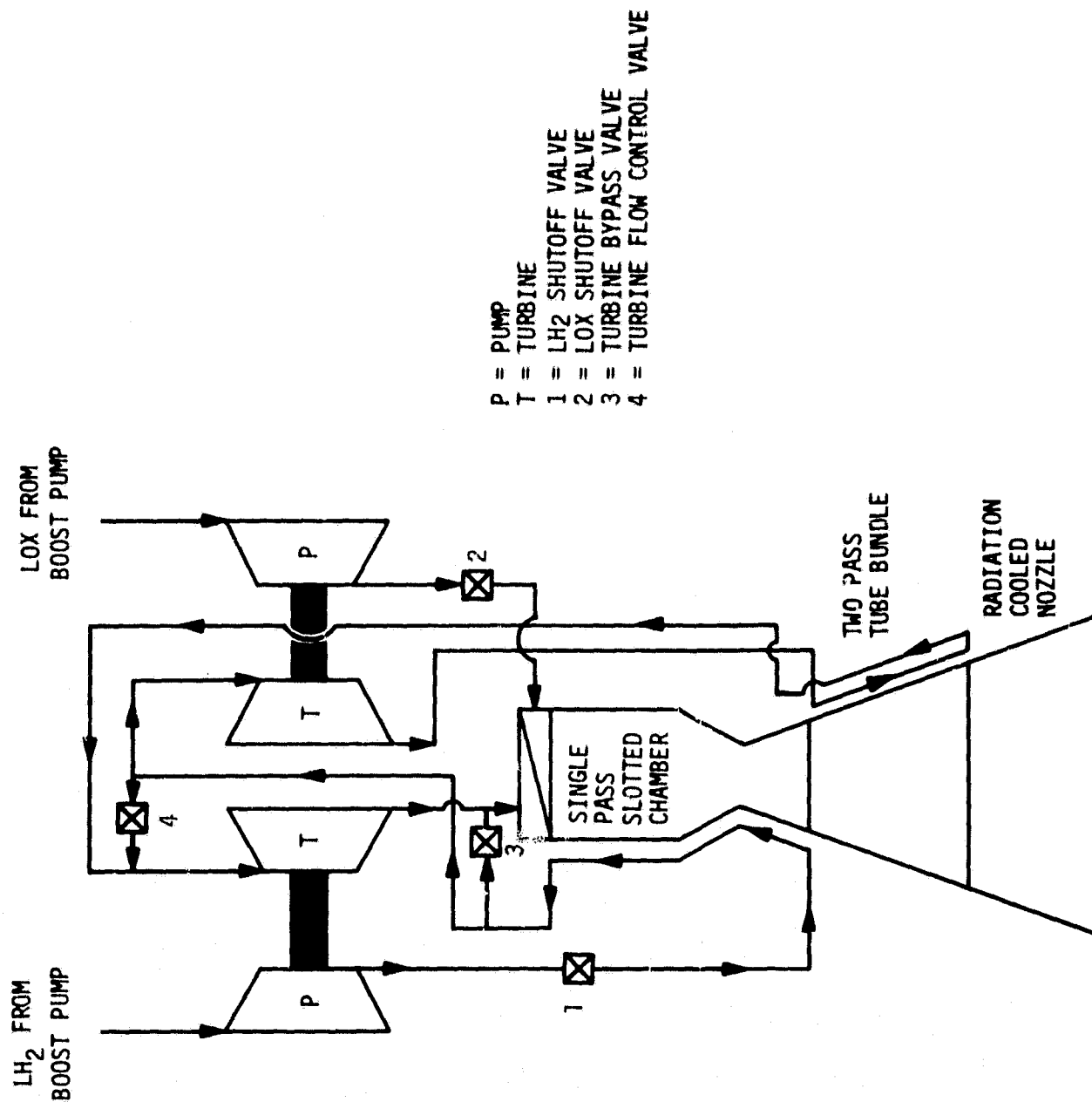
Figure 30. Turbine Exhaust Gas Reheat, Series Turbines, Advanced Expander
Cycle Flow Schematic

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TABLE XII

TURBINE EXHAUST REHEAT CYCLE COOLING EVALUATION

THRUST Klbf	INLET PRESSURE, PSIA	INLET TEMPERATURE, °R	CHAMBER ΔP, PSIA (1)	CHAMBER ΔP, PSIA (2)	COOLED AREA RATIO	NUMBER OF TUBES	TUBE ΔP, PSI	OUTLET TEMPERATURE, °R
10	2210	602	136	131	297	56	6.2	731
15	2040	484	95	92	186	58	4.8	590
20	1850	421	82	76	118	60	4.1	510

(1) Chamber cooled with 100% of the total hydrogen flow
(2) Chamber cooled with 85% of the total hydrogen flow

II, B, Cycle Optimization (cont.)

The results of the power balance analyses are displayed on
Tables XIII, XIV, and XV at thrust levels of 10K, 15K and 20K lb, respectively.
The cycle does have increased warm gas plumbing and these pressure drops have been
accounted for as noted by the line drops in the pressure schedules. Turbomachinery
efficiencies are the same as used in the series turbines evaluations. The tables
show that this cycle has slightly reduced fuel pump discharge pressure require-
ments when compared to the series turbines arrangement when compared at fixed
chamber pressures. These discharge pressures are:

Fuel Pump Discharge Pressure, psia

Thrust, lb	Series Turbines Cycle	Turbine Exhaust Gas Reheat Cycle
10,000	2695	2549
15,000	2473	2383
20,000	2225	2145

Performing the optimization for a given set of discharge
pressures results in the following comparisons.

Thrust, LB	Cycle	FUEL PUMP DISCHARGE PRESSURE, PSIA	CHAMBER PRESSURE, PSIA	ENGINE SPECIFIC IMPULSE, SEC
10	Series Turbines	2695	1300	480.2
15		2473	1200	477.2
20		2225	1100	474.2
10	Turbine Exhaust Gas Reheat	2695	1330	480.4
15		2473	1220	477.4
20		2225	1120	474.4

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TABLE XIII

TURBINE EXHAUST GAS REHEAT, SERIES TURBINES, POWER BALANCE (F = 10K LB)

POWER BALANCE
EXPANDER CYCLE:
SERIES TURBINES(1ST=UX CIRCUIT;2ND=FUEL CIRCUIT)
SEPARATE CHAMBER AND NOZZLE COOLANT JACKETS
BOOST PUMPS

PRESSURE SCHEDULE (PSIA)

	FUEL CIRCUIT	LOX CIRCUIT
1.PUMP INLET	51.00	46.86
2.PUMP PRESSURE RISE	2498.24	1561.43
3.PUMP DISCHARGE	2549.24	1605.03
4.LINE PRESSURE DROP	10.00	25.00
5.VALVE INLET	2539.24	1583.03
6.VALVE PRESSURE DROP	25.39	15.83
7.VALVE OUTLET	2513.85	1567.20
8.LINE PRESSURE DROP	30.00	15.00
9.CHAMBER COOLANT JACKET INLET	2483.85	...
10.CHAMBER COOLANT JACKET P DROP	131.00	...
11.CHAMBER COOLANT JACKET OUTLET	2352.85	...
12.LINE PRESSURE DROP	30.00	...
13.OX CIRCUIT TURBINE INLET	2322.85	...
14.OX CIRCUIT TURBINE PRESSURE RATIO	1.100	...
15.OX CIRCUIT TURBINE EXIT	2166.31	...
15A.LINE PRESSURE DROP	64.16	...
15B.NOZZLE COOLANT JACKET INLET	2102.15	...
15C.NOZZLE COOLANT JACKET P DROP	6.00	...
15D.NOZZLE COOLANT JACKET EXIT	2096.15	...
15E.LINE PRESSURE DROP	21.39	...
15F.FUEL CIRCUIT TURBINE INLET	2074.77	...
15G.FUEL CIRCUIT TURBINE PRESSURE RAT	1.401	...
15H.FUEL CIRCUIT TURBINE EXIT	1477.16	...
16.LINE PRESSURE DROP	37.87	...
17.TCA INJECTOR INLET	1439.26	1552.20
18.TCA INJECTOR PRESSURE DROP	119.89	232.83
19.TCA INJECTOR FACE	1319.37	1319.37
20.TCA PRESSURE DROP	19.37	19.37
21.CHAMBER PRESSURE	1300.00	1300.00

FLOWRATES (LBM/SEC)
TEMP DROP (DEGREES R)
CP(BTU/LB=R)
(FC=FUEL CIRCUIT)
(CC=OX CIRCUIT)
(T=S=TOTAL TO STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURBINE FLOW	2.80
2.OC TURBINE FLOW	2.80
3.FC TURB T DROP(T=S)	71.75
4.OC TURB T DROP(T=S)	18.31
5.FC TURB IN T(T)	730.60
6.FC TURB EXIT T(T)	698.23
7.OC TURB IN T(T)	619.00
8.OC TURB EXIT T(T)	601.60
9.DRIVE GAS (FROM CHAMBR)CP	3.538
10.DRIVE GAS GAMMA	1.395
11.DRIVE GAS(FROM NOZ)CP	3.538
12.DRIVE GAS(FROM NOZ)GAMMA	1.395
13.TURBINE BYPASS FLOW	.18

HORSEPOWERS AND EFFICIENCIES
(FC=FUEL CIRCUIT)
(OC=OX CIRCUIT)
(T=S=TOTAL TO STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURB HORSEPOW	731.37
2.OC TURB HORSEPOW	173.50
3.FL PUMP SHP	731.37
4.OX PUMP SHP	173.50
5.FC TURBINE EFF	.738
6.OC TURB EFF	.760
7.FUEL PUMP EFF	.620
8.OX PUMP EFF	.620
9.OX FLO	17.85
10.TOTAL FUEL FLO	2.97

$INPUT

TABLE XIV

TURBINE EXHAUST GAS REHEAT, SERIES TURBINES, POWER BALANCE (F = 15K LB)

POWER BALANCE
EXPANDER CYCLE
SERIES TURBINES(1ST-OX CIRCUIT;2ND-FUEL CIRCUIT)
SEPARATE CHAMBER AND NOZZLE COOLANT JACKETS
BOOST PUMPS

PRESSURE SCHEDULE (PSIA)

	FUEL CIRCUIT	LOX CIRCUIT
1.PUMP INLET	51.00	86.60
2.PUMP PRESSURE RISE	2332.37	1440.83
3.PUMP DISCHARGE	2383.37	1487.43
4.LINE PRESSURE DROP	10.00	25.00
5.VALVE INLET	2373.37	1462.43
6.VALVE PRESSURE DROP	23.73	14.92
7.VALVE OUTLET	2349.64	1447.50
8.LINE PRESSURE DROP	30.00	15.00
9.CHAMBER COOLANT JACKET INLET	2319.64	---
10.CHAMBER COOLANT JACKET P DROP	92.00	---
11.CHAMBER COOLANT JACKET OUTLET	2227.64	---
12.LINE PRESSURE DROP	30.00	---
13.OX CIRCUIT TURBINE INLET	2197.58	---
14.OX CIRCUIT TURBINE PRESSURE RATIO	1.106	---
15.OX CIRCUIT TURBINE EXIT	2038.00	---
15A.LINE PRESSURE DROP	60.96	---
15B.NOZZLE COOLANT JACKET INLET	1977.04	---
15C.NOZZLE COOLANT JACKET P DROP	5.06	---
15D.NOZZLE COOLANT JACKET EXIT	1972.28	---
15E.LINE PRESSURE DROP	20.32	---
15F.FUEL CIRCUIT TURBINE INLET	1952.12	---
15G.FUEL CIRCUIT TURBINE PRESSURE RAT	1.470	---
15H.FUEL CIRCUIT TURBINE EXIT	1362.03	---
16.LINE PRESSURE DROP	34.92	1432.80
17.TCA INJECTOR INLET	1327.10	214.92
18.TCA INJECTOR PRESSURE DROP	109.22	1217.88
19.TCA INJECTOR FACE	1217.88	17.88
20.TCA PRESSURE DROP	17.88	1200.00
21.CHAMBER PRESSURE	1200.00	

FLOWRATES (LBM/SEC)
TEMP DROP (DEGREES R)
CP(BTU/LB-R)
(FC=FUEL CIRCUIT)
(OC=OX CIRCUIT)
(T-S=TOTAL TO STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURBINE FLOW	8.22
2.OC TURBINE FLOW	8.22
3.FC TURB T DROP(T-S)	51.02
4.OC TURB T DROP(T-S)	45.88
5.FC TURB IN T(T)	680.38
6.FC TURB EXIT T(T)	548.62
7.OC TURB IN T(T)	895.00
8.OC TURB EXIT T(T)	884.38
9.DRIVE GAS (FROM CH-B)CP	3.716
10.DRIVE GAS GAMMA	1.384
11.DRIVE GAS(FROM NOZ)CP	3.570
12.DRIVE GAS(FROM NOZ)GAMMA	1.395
13.TURBINE BYPASS FLOW	.27

HORSEPOWERS AND EFFICIENCIES
(FC=FUEL CIRCUIT)
(OC=OX CIRCUIT)
(T-S=TOTAL TO STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURB HORSEPOW	975.58
2.OC TURB HORSEPOW	235.57
3.FL PUMP SHP	975.58
4.OX PUMP SHP	235.57
5.FC TURBINE EFF	.758
6.OC TURB EFF	.705
7.FUEL PUMP EFF	.655
8.OX PUMP EFF	.636
9.OX FLO	26.94
10.TOTAL FUEL FLO	4.49

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TABLE XV

TURBINE EXHAUST GAS REHEAT, SERIES TURBINES, POWER BALANCE (F = 20K LB)

POWER BALANCE
EXPANDER CYCLE:
SERIES TURBINES(1ST=OX CIRCUIT;2ND=FUEL CIRCUIT)
SEPARATE CHAMBER AND NOZZLE COOLANT JACKETS
BOOST PUMPS

PRESSURE SCHEDULE (PSIA)

	FUEL CIRCUIT	LOX CIRCUIT
1.PUMP INLET	51.00	86.60
2.PUMP PRESSURE RISE	2093.50	1320.22
3.PUMP DISCHARGE	2144.50	1366.82
4.LINE PRESSURE DROP	10.00	25.00
5.VALVE INLET	2134.50	1341.82
6.VALVE PRESSURE DRCP	21.34	13.42
7.VALVE OUTLET	2113.15	1328.40
8.LINE PRESSURE DROP	30.00	15.00
9.CHAMBER COOLANT JACKET INLET	2083.15	---
10.CHAMBER COOLANT JACKET P DRCP	76.00	---
11.CHAMBER COOLANT JACKET OUTLET	2007.15	---
12.LINE PRESSURE DFOP	30.00	---
13.OX CIRCUIT TURBINE INLET	1977.15	---
14.OX CIRCUIT TURBINE PRESSURE RATIO	1.107	---
15.OX CIRCUIT TURBINE EXIT	1832.28	---
15A.LINE PRESSURE CRCP	55.81	---
15B.NOZZLE COOLANT JACKET INLET	1776.48	---
15C.NOZZLE COOLANT JACKET P DRCP	4.00	---
15D.NOZZLE COOLANT JACKET EXIT	1772.48	---
15E.LINE PRESSURE DROP	18.60	---
15F.FUEL CIRCUIT TURBINE INLET	1753.87	---
15G.FUEL CIRCUIT TURBINE PRESSURE RAT	1.441	---
15H.FUEL CIRCUIT TURBINE EXIT	1248.68	---
16.LINE PRESSURE DROP	32.02	---
17.TCA INJECTOR INLET	1216.66	1313.40
18.TCA INJECTOR PRESSURE DROP	100.27	197.01
19.TCA INJECTOR FACE	1116.39	1116.39
20.TCA PRESSURE DHCP	16.39	16.39
21.CHAMBER PRESSURE	1100.00	1100.00

FLOWRATES (LBM/SEC)
TEMP DRCP (DEGREES R)
CP(BTU/LBM-R)
(FC=FUEL CIRCUIT)
(OC=OX CIRCUIT)
(T-S=TOTAL TC STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURBINE FLOW	5.66
2.OC TURBINE FLOW	5.66
3.FC TURB T DROP(T-S)	50.06
4.OC TURB T DROP(T-S)	11.99
5.FC TURB IN T(T)	509.77
6.FC TURB EXIT T(T)	471.22
7.OC TURB IN T(T)	430.00
8.OC TURB EXIT T(T)	420.77
9.DRIVE GAS (FROM CHMBR)CP	3.832
10.DRIVE GAS GAMMA	1.307
11.DRIVE GAS(FROM NOZ)CP	3.692
12.DRIVE GAS(FROM NOZ)GAMMA	1.395
13.TURBINE BYPASS FLOW	.36

HORSEPOWERS
AND EFFICIENCIES
(FC=FUEL CIRCUIT)
(OC=OX CIRCUIT)
(T-S=TOTAL TO STATIC TEMP)
(T=TOTAL TEMP)

1.FC TURB HORSEPOW	1140.13
2.OC TURB HORSEPOW	283.39
3.FL PUMP SHP	1140.13
4.OX PUMP SHP	283.39
5.FC TURBINE EFF	.770
6.OC TURB EFF	.770
7.FUEL PUMP EFF	.675
8.OX PUMP EFF	.650
9.OX FLO	36.15
10.TOTAL FUEL FLO	6.03

II, B, Cycle Optimization (cont.)

The small reductions in discharge pressure requirements or
the 0.2 sec increase in performance are not considered significant enough to
offset the additional cycle complexity and component interactions and warrant
a selection of this cycle over a series turbines drive.

4. Cycle Analysis Summary

The results of all power balance and performance/weight
trade analyses are summarized on Tables XVI and XVII.

Table XVI shows that the largest benefit is obtained with a
series turbine arrangement rather than parallel turbines. Further reductions
in fuel pump discharge pressure requirements and turbine pressure ratios which
reduce cycle sensitivity can be obtained through turbine exhaust heat regenera-
tion or turbine exhaust reheat schemes.

Table XVII compares the performance of the new cycles to the
original parallel turbines baseline. Relative payloads are all computed using
the parallel turbines cycle as a baseline for each thrust level. No attempt is
made to compare the relative payload capability of the various thrust levels.
This table shows that the turbine exhaust reheat cycle has the highest per-
formance potential but the series turbines arrangement offers about the same
capability.

TABLE XVI

CYCLE OPTIMIZATION POWER BALANCE DATA SUMMARY
(FIXED CHAMBER PRESSURES)

THRUST, LB	CHAMBER PRESSURE, PSIA	CYCLE	FUEL PUMP DISCHARGE PRESSURE, PSIA	TURBINE PRESSURE RATIO FUEL	TURBINE PRESSURE RATIO OX.
10,000	1300	Parallel Turbines	3545	2.284	2.284
15,000	1200		3174	2.229	2.229
20,000	1100		2764	2.113	2.113
10,000	1300	Series Turbines	2695	1.548	1.103
15,000	1200		2473	1.544	1.109
20,000	1100		2225	1.514	1.109
10,000	1300	Turbine Exhaust Heat Regeneration With Series Turbines	2645	1.356	1.07?
15,000	1200		2331	1.337	1.075
20,000	1100		2036	1.233	1.058
10,000	1300	Turbine Exhaust Heat Regeneration With Parallel Turbines	2936	1.620	1.620
10,000	1300	Turbine Exhaust Reheat With Series Turbines	2549	1.441	1.100
15,000	1200		2383	1.470	1.106
20,000	1100		2145	1.440	1.107

TABLE XVII

CYCLE PERFORMANCE OPTIMIZATION DATA SUMMARY
(FIXED FUEL PUMP DISCHARGE PRESSURES)

THRUST, LB	CYCLE	FUEL PUMP DISCHARGE PRESSURE, PSIA	CHAMBER PRESSURE, PSIA	ENGINE SPECIFIC IMPULSE, SEC	ENGINE WEIGHT, LB	AMOTV RELATIVE PAYLOAD, LB
10,000	Parallel Turbines	3545	1300	480.2	447	0
15,000		3174	1200	477.2	502	0
20,000		2764	1100	474.2	554	0
10,000	Series Turbines	3545	1480	481.2	455	+64
15,000		3174	1345	478.1	514	+53
20,000		2764	1225	475.1	567	+51
10,000	Turbine Exhaust Heat Regeneration With Series Turbines	3545	1490	481.2	492	+24
15,000		3174	1375	478.3	581	- 7
20,000		2764	1270	475.4	710	-84
10,000	Turbine Exhaust Heat Regeneration With Parallel Turbines	3545	1430	480.9	488	+ 6
10,000	Turbine Exhaust Reheat With Series Turbines	3545	1510	481.3	457	+69
15,000		3174	1365	478.2	520	+53
20,000		2764	1245	475.3	572	+61

II, Advanced Expander Cycle Engine Optimization (cont.)

C.   ENGINE CYCLE SENSITIVITY ANALYSIS

The objective of this subtask was to evaluate the sensitivity of baseline engine cycle power balance to changes in pump and turbine efficiencies, component pressure drops, turbine inlet temperature and turbine by-pass flow. Statistical deviations in these parameters were either established from historical data, where available, or assumed to establish their effect upon the engine operating chamber pressure.

Data on Titan second stage production engines in support of the Titan III B/C/D vehicles show a one sigma variation of ± 1.06%, 1.69% and 1.64%, for the oxidizer pump, fuel pump and turbine efficiencies, respectively. This data covered 54 engines over three production contracts and is assumed to be representative for the OTV.[1] The worst case has been assumed for the pumps (i.e. 1.69% instead of 1.06%). Three sigma variations in the pump and turbine efficiencies result in:

> 3 Sigma Pump Efficiency Variation: ± 5.07%
> 3 Sigma Turbine Efficiency Variation: ± 4.92%

Because these numbers are so close, deviations of ± 5% were used in the study for all turbomachinery components.

Component resistance variations were also obtained from the Titan III report. Typical values are:

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(1) Titan III B/C/D Stages I and II Pressure Schedules, Report 9113:3324, ALRC, 15 Oct 1969

II, C, Engine Cycle Sensitivity Analysis (cont.)

	%	
	One Sigma	Three Sigma
Coolant Jacket Resistance	$\pm$ 6	$\pm$ 18
Fuel Injector Resistance	$\pm$ 4	$\pm$ 12
Oxidizer Injector Resistance	$\pm$ 3	$\pm$ 9

Resistance is proportional to the pressure drop (ΔP) times the fluid density (ρ) divided by the flowrate ($\dot{\omega}$) squared (i.e. $R = \frac{\Delta P}{\dot{\omega}^2} \times \rho$). Assuming constant flow and densities, the above variations were used to approximate the deviations in component pressure drops. Two pressure drop deviations were evaluated in the fuel system to establish the affect of pressure drops upstreams and downstream of the turbines.

Turbine inlet temperature and by-pass flowrate variations were also evaluated. Because no historical statistical variations were readily available, the turbine inlet temperature was varied $\pm$ 5% to establish its affect and the turbine by-pass flowrate was assumed as 3% and 9% about the 6% nominal value.

The engine cycle analyzed in this task is the series turbines expander cycle. Again, the baseline chamber pressures used in the analyses were selected in the initial Phase "A" OTV study efforts. The nominal component parameters at each thrust level and the component deviations considered are shown on Table XVIII.

The results of this study subtask are shown on Figures 31, 32, 33 and 34. Figure 31 shows that a $\pm$ 5% deviation in the fuel pump on turbine efficiency results in approximately a $\pm$ 2.7% variation in chamber pressure

TABLE XVIII

NOMINAL COMPONENT DATA FOR CYCLE SENSITIVITY ANALYSIS
SERIES TURBINES CYCLE

Thrust KLB	Chamber Pressure, Psia	Fuel Pump Efficiency, %	Oxidizer Pump Efficiency, %	Fuel Pump Turbine Efficiency, %	Oxidizer Pump Turbine Efficiency, %	Chamber Coolant Jacket Pressure Drop, Psi	Injector Fuel Pressure Drop, Psi	Injector Oxidizer Pressure Drop, Psi	Fuel Turbine Inlet Temp, °R	Turbine By-Pass Flow, % of Fuel
10	1300	62	62	73	76	131	118	233	653	6
15	1200	65.5	63.6	75	76.5	92	109	215	535	6
20	1100	67.5	65.0	77	77	76	100	197	463	6
Deviation		± 5%	± 5%	± 5%	± 5%	± 18%	± 12%	± 9%	± 5%	3&9
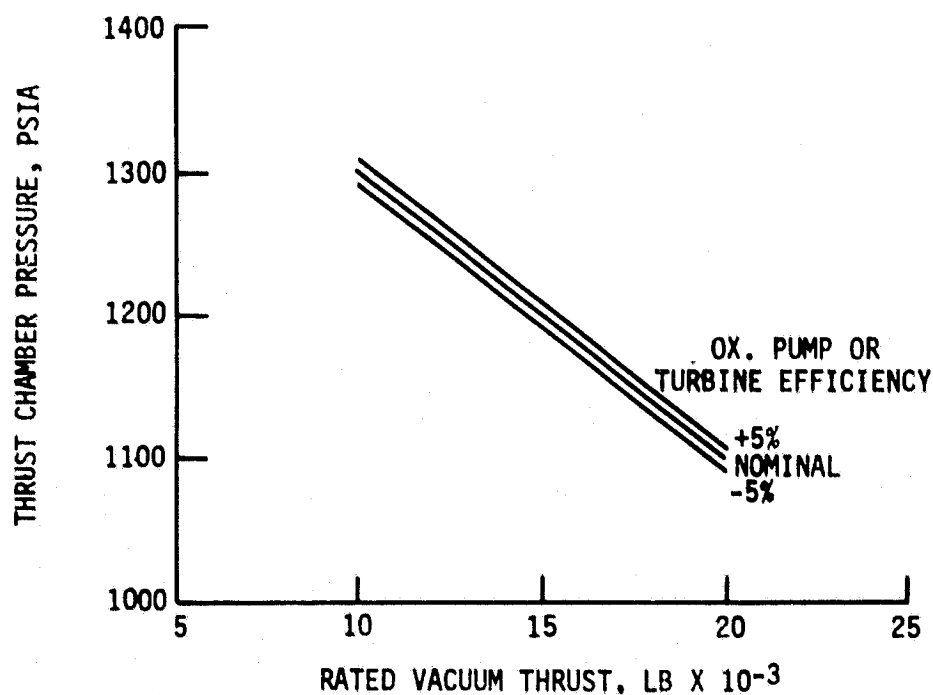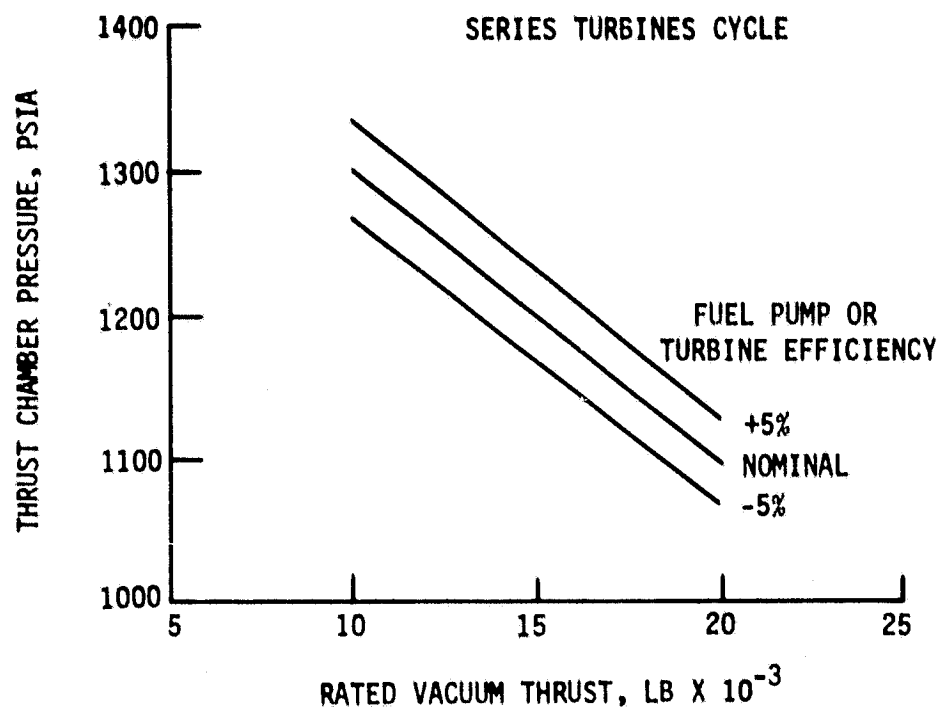
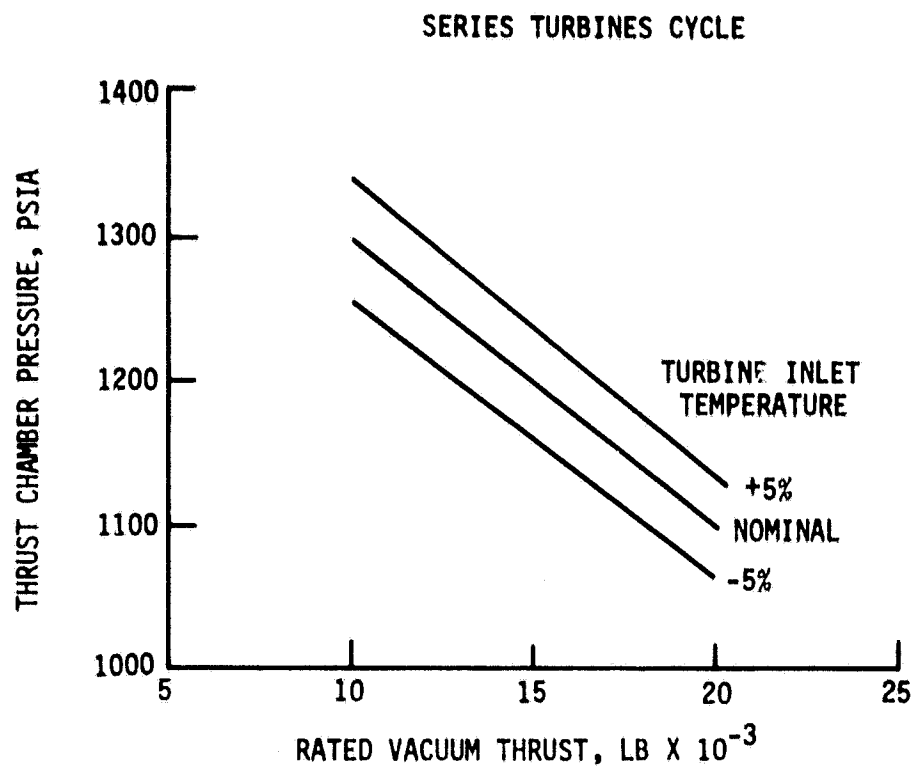Figure 31.   Expander Cycle Sensitivity to Turbomachinery Performance Variations
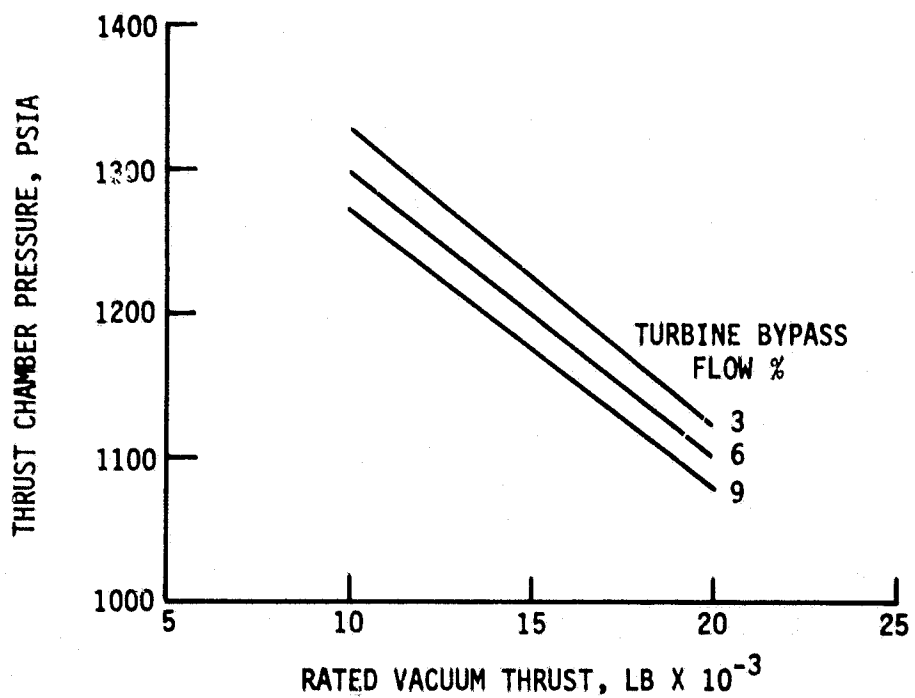
Figure 32. Expander Cycle Sensitivity to Turbine Inlet Temperature and By-pass Flow Variations
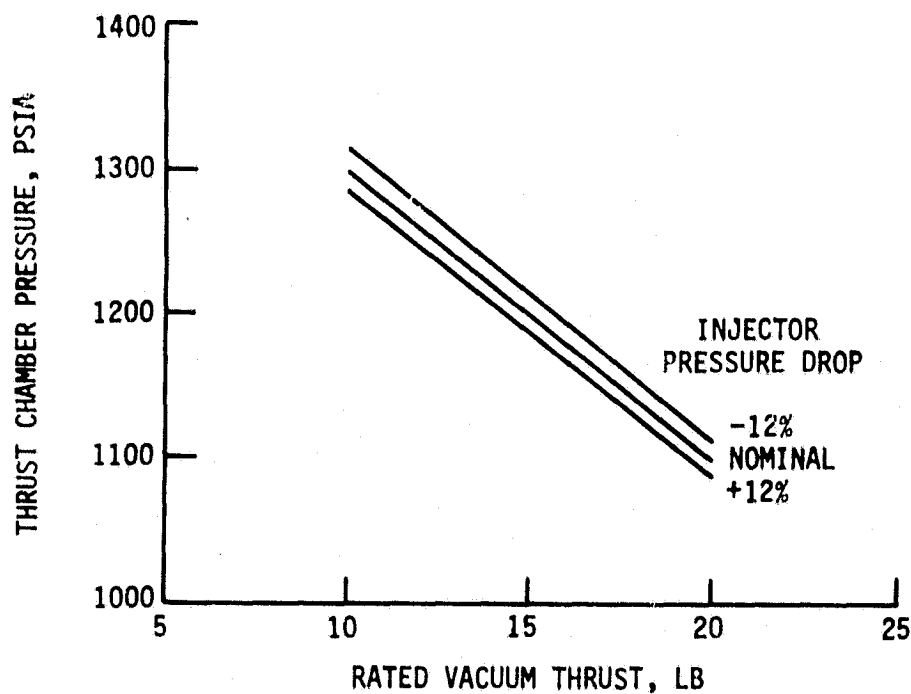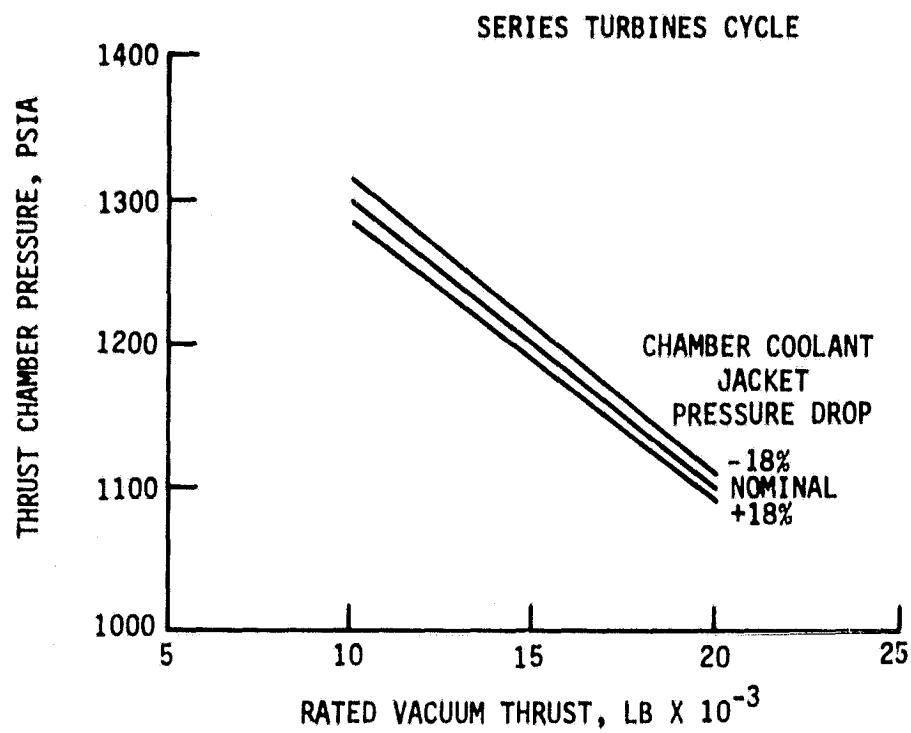
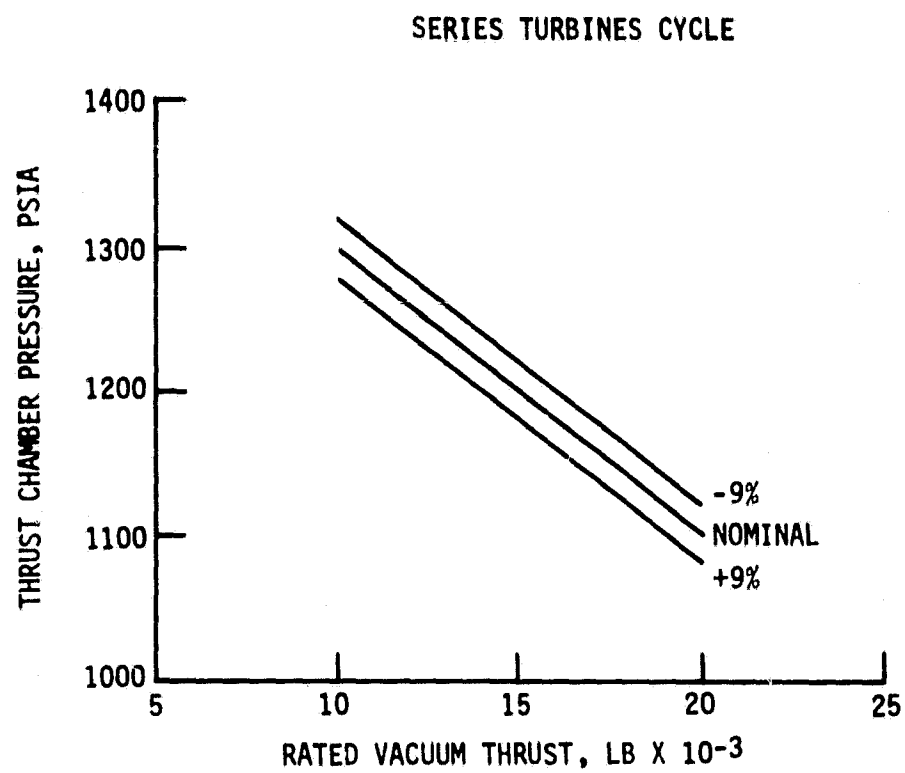Figure 33. Expander Cycle Sensitivity to Fuel System Component Pressure Drop Variations

SERIES TURBINES CYCLE

Figure 34. Expander Cycle Sensitivity to Oxidizer System Component Pressure
Drop Variations

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over the entire thrust range. The effect of the oxidizer pump and turbine efficiency is less because this is the low horsepower system. A $\pm$ 5% deviation in the oxidizer pump or turbine efficiency only causes approximately a $\pm$ 0.6% variation in the engine thrust chamber pressure as shown by Figure 31.

Figure 32 shows the affect of turbine inlet temperature and turbine by-pass flow rate upon the cycle power balance. A $\pm$ 5% deviation in the fuel turbine inlet temperature creates approximately a $\pm$ 3.5% variation in chamber pressure. A reduction in turbine by-pass flowrate from 6% of the total fuel flowrate to 3% increases the engine thrust chamber pressure by 2% while an increase in by-pass flow to 9% causes a 2% reduction in chamber pressure. Therefore, the 6% by-pass flowrate can make up for component deviations that would otherwise cause a total chamber pressure change of 4%.

Figure 33 shows the expander cycle engine sensitivity to fuel system pressure drops upstream and downstream of the turbines. A $\pm$ 18% deviation in the combustion chamber coolant jacket pressure drop causes a $\pm$ 1% change in chamber pressure. The $\pm$ 12% variation in the fuel system injector pressure drop also results in about a $\pm$ 1% change in chamber pressure.

Figure 34 shows the affect of a $\pm$ 9% deviation in the oxidizer system injector pressure drop. This results in approximately a $\pm$ 1.6% change in chamber pressure over the entire thrust range.

All variations discussed in the previous paragraphs assume only single component deviations. The performance of a component was varied while the others were held at their nominal values. A worse case was also analyzed. The worse case consisted of reducing the fuel pump, fuel pump turbine, oxidizer pump and oxidizer pump turbine efficiencies by 5%, reducing the turbine inlet

II, C, Engine Cycle Sensitivity Analysis (cont.)

temperature by 5%, increasing the coolant jacket pressure drop by 18% and increasing the fuel system injector pressure drop by 12%. The turbine by-pass flow was fixed at 6%. This resulted in a 13.4% decrease in thrust chamber pressure at a thrust level of 15K lb. Thus, the chamber pressure variations are almost additive as shown below.

	Deviation %	Chamber Pressure Variation %
Fuel Pump Efficiency	-5	2.7
Oxidizer Pump Efficiency	-5	0.6
Fuel Turbine Efficiency	-5	2.7
Oxidizer Turbine Efficiency	-5	0.6
Turbine Inlet Temp	-5	3.5
ΔP Coolant Jacket	-18	1.0
ΔP Fuel Injector	-12	1.0
	Total	12.1

This is a worse case deviation and not all predictions would be expected to be at their worse case 3 sigma values. The drivers are obviously the fuel turbomachinery efficiencies and turbine inlet temperature.

If component performance is not as predicted, necessitating a change in operating chamber pressure level at a given thrust, the engine performance (I_s) and weight will only be slightly affected. Figure 35, extracted from the initial Phase A efforts, shows the variation of engine weight with the operating pressure level for a fixed engine envelope. The figure shows that the weight variations are not significant. The variation of engine performance about the nominal chamber pressure levels is shown on Figure 36.
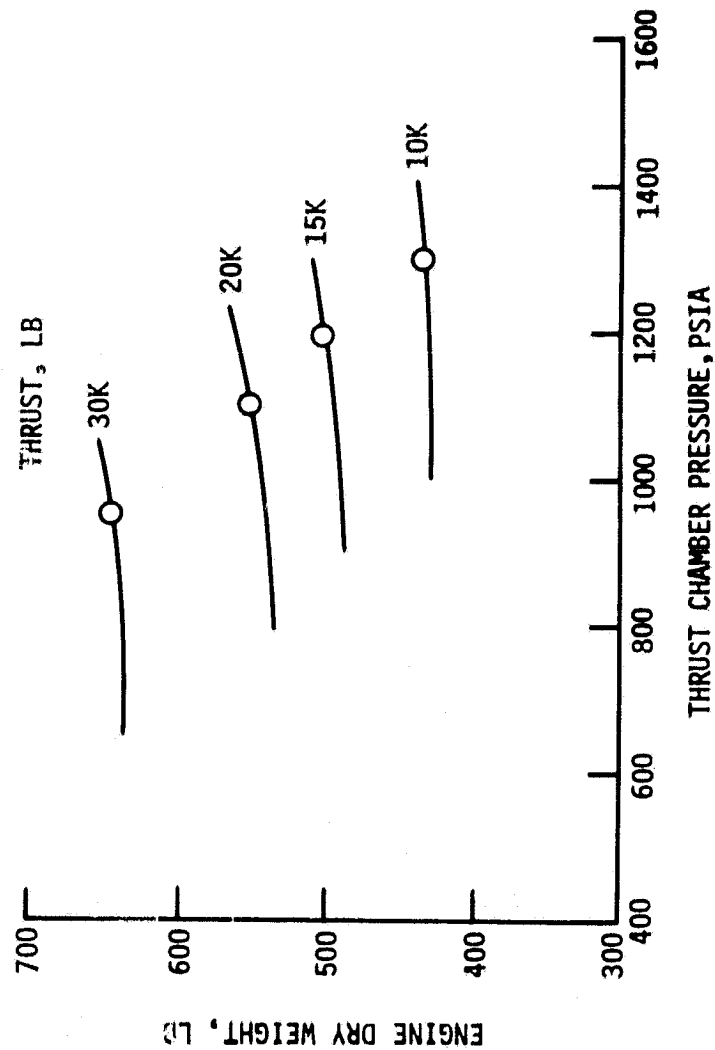
NOMINAL MR= 6.0
STOWED ENGINE LENGTH = 60 IN.

Figure 35. Advanced Expander Cycle Engine Weight vs Chamber Pressure

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NOMINAL O/F = 6.0
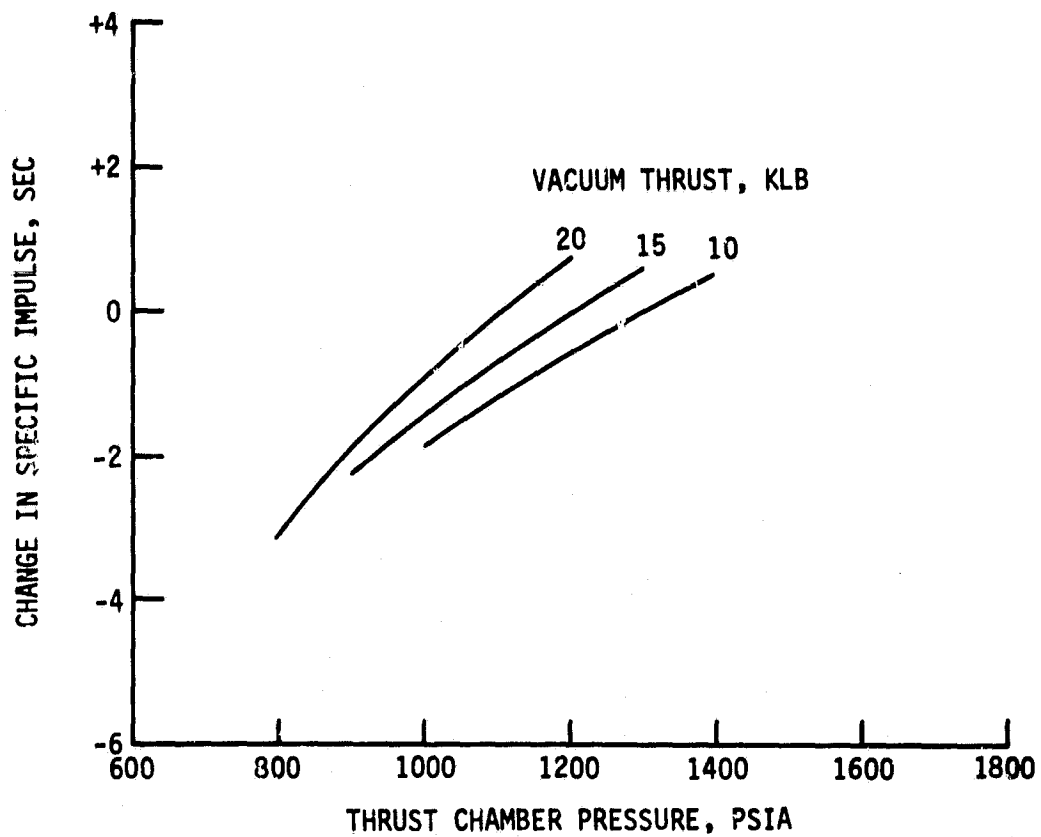STOWED ENGINE LENGTH = 60 IN.

Figure 36. Effect of Thrust Chamber Pressure Upon Delivered Engine Specific Impulse

II, C, Engine Cycle Sensitivity Analysis (cont.)

The figure shows that a 10% variation in the operating thrust chamber pressure
level results in less than a 1 (one) sec. change in delivered specific impulse.
The nominal performance values at each thrust level are:

Vac. Thrust, KLB	Thrust Chamber Pressure, Psia	Engine Delivered Specific Impulse, Sec.	Nozzle Area Ratio
10	1300	480.2	792
15	1200	477.2	473
20	1100	474.2	322

II, Advanced Expander Cycle Engine Optimization (cont.)

D. CHILLDOWN/START PROPELLANT CONSUMPTIONS

Engine chilldown/start propellant consumptions estimates were made assuming a tank-head idle mode condition. Tank-head idle mode is a pressure fed mode of operation with saturated propellants in the tanks. Its purpose is to thermally condition the engine without non-propulsive dumping of the propellants.

Chilldown propellant estimates were made by reviewing and scaling the results of past studies. Those analyses utilized are reported in References 2, 3, 6 and 7. Reference 3 (OOS Studies) presents scaling relationships and results that require empirical data for correlation while Reference 2 (RL-10 Derivative Study) analyzes specific design points and has the benefit of emperical data to adjust analytical models. Therefore, the predictions of Reference 2 were used to adjust the OOS models. The adjusted Ref. 2 data are presented on Figure 37 and the results are summarized on Table XIX.
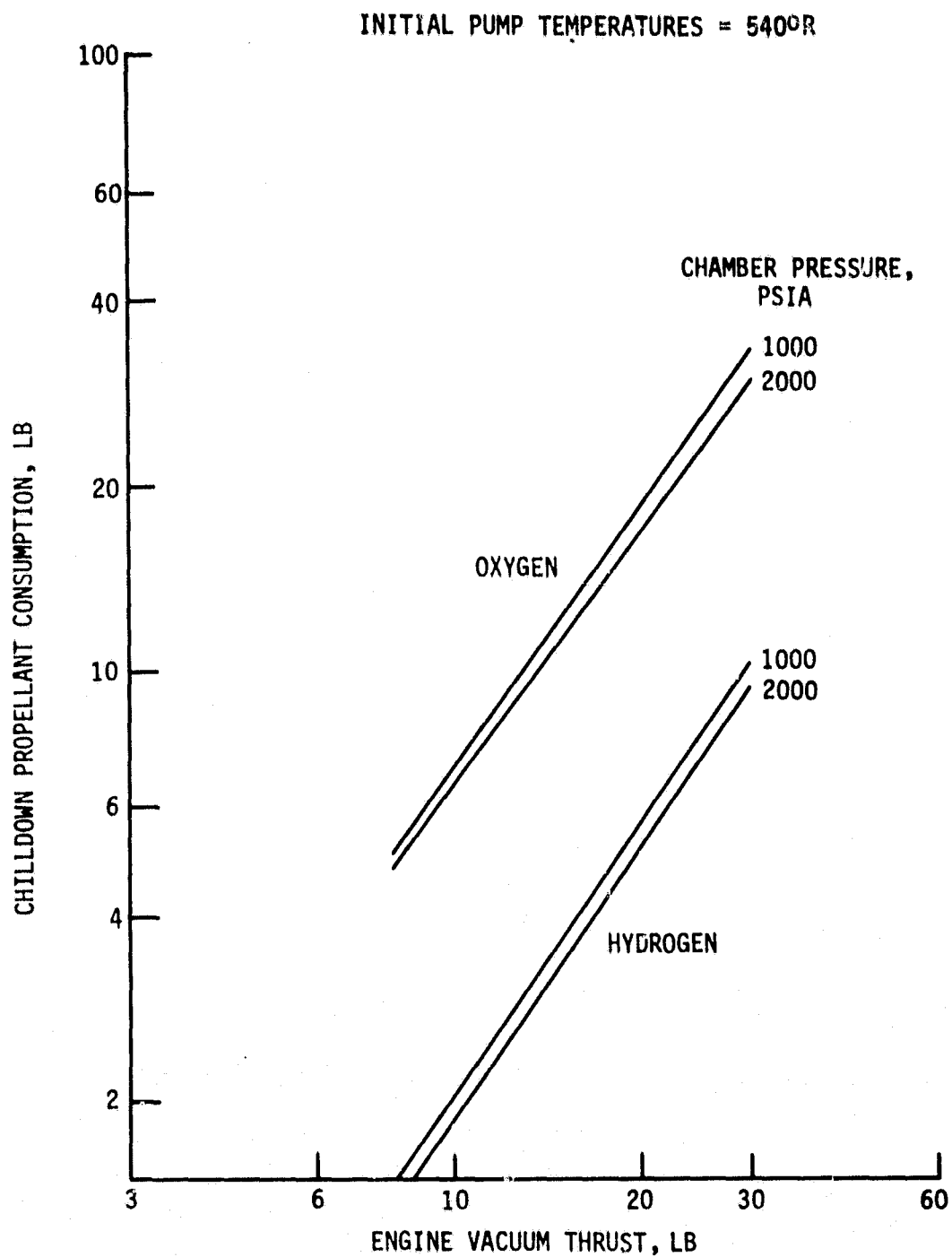
Figure 37. Chilldown Propellant Consumption Parametric Data

TABLE XIX

CHILLDOWN PROPELLANT CONSUMPTION ESTIMATES
INITIAL PUMP TEMPERATURES = 540°R

Thrust lb	Chamber Pressure psia	Total Propellant Consumption lb
10,000	1300	9.0
15,000	1200	16.0
20,000	1100	24.0

REFERENCES

1. <u>Orbit Transfer Vehicle (OTV) Engine Phase "A" Study</u>, Final Report, Volume II: Study Results, Contract NAS 8-32999, ALRC, 29 June 1979.

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3. Luscher. W.P.. <u>Orbit-to-Orbit Shuttle Engine Design Study</u>, Final Report, Books 1 through 4, Contract F04611-71-C-0040, AFRPL TR-72-45, ALRC, May 1972.

4. Dennies, P.C., Marker, H.E., and Yost, M.C., <u>Advanced Thrust Chamber Technology</u>, Final Report, Contract NAS 3-17825, NASA CR-135221, Rocketdyne, 5 July 1977.

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6. Zachary, A.T., <u>Advanced Space Engine Preliminary Design</u>, Final Report, Contract NAS 3-16751, NASA CR-121236, Rocketdyne, October 1973.

7. Bradie, R.E., and Cuffe, J.P.B., <u>Advanced Space Engine Preliminary Design</u>, Final Report, Contract NAS 3-16750, NASA CR-121237, Pratt and Whitney, December 1973.